THE IMPACT OF PAST GOLD MINING ACTIVITIES ON THE SHUBENACADIE RIVER HEADWATERS ECOSYSTEM

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SUMMARY

Gold mining operations were carried out in the Waverley area beginning in the 1860's and continuing until the 1930's. These operations have cause a major problem which has only become apparent in the last few years, that of arsenic (As) and mercury (Hg) contamination in the aquatic ecosystem. Arsenic occurs naturally in gold bearing ores and was released from the bedrock by rock crushing and consequent exposure of this to weathering. The refining process used a mercury amalgamation method for extracting gold and it has been estimated that over 1000 kg of Hg were deposited in the study area over the course of operations. An additional past source of mercury could have been a manufacture of explosives located near the Power Mill Lake. Based on the above facts, three main goals were established for this study. The first was to trace the sites where refining operations were carried out and the location of the tailing sites. The second was to characterize the levels of Hg and As in sediments as these related to past industrial acctivities; and the third was to determine the As and Hg pathways between water, suspended and bottom sediments and fish.

The water quality of the studied lakes and their interconnecting streams was generally typical for south central Nova Scotia. There is an obvious contribution of sodium chloride (NaCl) from marine spray and in the lower parts of the watershed a more important contribution from road salting operations. None of the

major ions exceeded any water quality objectives for drinking water or aquatic life. Metal levels in the waters of the basin are all fairly low except for levels of As. Though measured As levels were all within drinking water and aquatic life standards, values measured at the Muddy Pond outflow which empties near the Lake Thomas swimming beach were very close to accepted limits. No seasonal trends in As concentration were detected during this study. Hg concentration in all water samples was below the detection limit of 0.02 $\mu g.L^{-1}$. Based on historical data the study lakes seemed to be more acid in 1983 than in 1976. Should this trend be real then increasing acidification may increase the release of metals from the sediment and suspended solids and consequently affect the quality of other parameters.

Sediments collected from the Muddy Pond, Lake Thomas and Powder Mill Lake were contaminated by As, Hg, Pb and Zn in various degrees. On the other hand sediments collected from Lakes Third, Perry and Loon were uncontaminated and only the top 2 cm of the sediment from Three Mile Lake contained elevated concentrations of Pb and Zn. The highest contamination of the sediment by Hg and As was found in Powder Mill Lake and Muddy Pond, respectively. Concentration profiles of As in Lakes Thomas, Powder Mill and Muddy Pond indicated that the sediment contaminated by these elements is buried by a layer of less contaminated material. However, concentration profiles of Hg in Powder Mill Lake sediment suggest a continuous input of this element into the lake. A statistical relationship was observed between the concentrations of Hg and Au in sediments collected from

Muddy Pond and Powder Mill Lake. This indicates that the input of some Hg originates from the amalgamation process used for gold refining during the mining operations.

Rates of sediment deposition into the lakes increased during the past 60 years. During this period sediment character changed from rich brown organic uncontaminated material to more inorganic material, contaminated by the mining wastes.

In addition to the input from the shore, contaminants are transported by suspended sediment in connecting streams from one lake to the other. The investigation showed that significant quantities of particulate As and Hg are being transported through the lake chain. However, the changes in the mean monthly discharge of the creeks affects the quantities of transported As and Hg. The greatest quantities of As and Hg in suspended solids were transported from Lake Thomas into Lake Fletcher. A significant transport of As in ionic form in the water was observed in addition to that by suspended solids. The greatest quantity of As transported by water was from Muddy Pond into Lake Thomas. No transport of dissolved Hg was observed in any creek. High concentration of Fe and Mn indicated that As may be associated in suspended solids with these two elements. Observed solubilization of Fe and Mn from sediments during lakes stratification and anoxic conditions may play an important role in the transportation processes. A significant transport of Pb and Zn in addition to the transport of As and Hg by suspended solids was observed from Muddy Pond into Lake Thomas.

A preliminary study of metal concentrations in fish revealed levels of Hg in fish from Lakes Thomas, Powder Mill and William up to four times higher than the Federal Health Protection Branch Administrative Guideline for fish for human consumption, with the highest values being found in white perch. Because no other components of the biota were studied, nor were the fish collected in high enough numbers for a thorough analysis of species and size differences, additional studies will be conducted over the next two years to ascertain the significance of these results.

All reports show that As and Hg are the parameters of greatest concern in the surface waters of the study area. Both elements most likely follow similar pathways, from tailings and mine sites through sediment and suspended matter and to a lesser extent, to fish, though they do not go through the ecosystem at the same rates. There were no obvious seasonal changes to the total Hg and As concentrations in the water. This is probably deceptive, as reduced water flows and anoxic conditions in the lakes in summer must modify the flushing rates and should change the species composition of both As and Hg. At present, some of the lakes studied, especially Powder Mill, Muddy Pond and Thomas, seem to be in precarious positions in terms of sensitivity to further input of contaminants. Major disturbances in their watersheds, changing their flushing regimes, dredging bottom sediment or increasing organic loading which could lead to more extended periods of anoxia, all could have major impact on both water and biota in the study area and further downstream.

RECOMMENDATIONS

1. The present study showed the levels of As in the Muddy Pond outflow and Lake Thomas approaching the maximum allowable values for drinking water. The National Water Research Institute, Burlington, Ontario, is planning to continue the study of As concentration in this area. In addition, concentrations of different species of dissolved As will be investigated during the lakes stratification. Particular attention will be directed towards determination of the ratio of more toxic As(III) to less toxic As(V), to assess the overall toxicity to the biota in the lakes.
2. The sediments and fish in Powder Mill Lake have been shown to be contaminated with high amounts of mercury and lesser levels of arsenic. The concentration of mercury was below the detection limit in all water samples collected during the study period from the lakes. However, the sampling was carried out only every second month. Increased sampling density would be desirable to supplement the information on mercury concentration in lakes water obtained during this study.
3. Solubilization of Fe and Mn occurred during anoxic conditions in the stratified lakes in summer. In addition, high concentrations of these two elements were found in the suspended solids in creeks together with high concentrations of As and other metals. Solubilization of As and other metals from sediments,

precipitation mechanism and concentration of various species of dissolved and particulate Fe and Mn in the lakes will be studied by the National Water Research Institute, Burlington, Ontario, during the next two years to investigate if a relationship exists between the transport of As and metals and solubilization/ precipitation of Mn and Fe.

4. The present study showed accumulation of Hg in certain fish species. A study of the bioaccumulation of As and Hg in the complete food chain in the lakes started in 1984/85 and will continue in next two years.

5. Material excavated from tailings deposits and other mine wastes was often used in construction of roads and railroad beds. Inland Waters Directorate, Water Quality Branch, Atlantic Region together with the National Water Research Institute, Burlington, Ontario, are making plans to investigate the leaching and pathways of As and Hg from known fill sites. In particular, contamination of groundwater by these leachates will be looked at.

6. The data obtained by this study indicate that the contaminated sediment in the lakes recently started to become covered with less contaminated material. Gold mining wastes were identified at many sites in the study area. Disturbance of these wastes would bring about further mobilization of As, Hg and other contaminants and their accumulation in the sediment on the bottom of the lakes.

7. The sediment in Muddy Pond is a source of particulate As, Pb and Hg and a significant source of dissolved As for Lake Thomas. We recommend to prevent the inflow of suspended sediment and water from the Muddy Pond into Lake Thomas.
8. Dredging of sediments from Lakes Thomas, William, Fletcher and Powder Mill may become necessary in the future for improving canoeing routes. Testing of mobilization of As, Hg and other metals from sediments will be necessary prior to the dredging operations. Environmental impact assessment of the dredging and dredged material disposal should include the effect of resuspension of contaminated sediment on the water quality and a recommendation of a proper disposal of the contaminated sediment.
9. A number of tailing piles have been identified throughout the headwater lakes system. Should homes or industries using groundwater wells be located close to the piles, then groundwater mapping of areas potentially affected should be done.
10. More frequent monitoring of nitrogen, phosphorus, chlorphyll a and dissolved oxygen is recommended to assess the productivity of the lakes, phosphorus loadings from different sources and trophic status of the Shubenacadie headwater lakes.

FOREWORD

The Shubenacadie River headwater lakes basin is bordered on the east by the Halifax/Dartmouth metropolitan area with the uppermost lake in this basin, Loon Lake, being in the suburbs of Dartmouth. Halifax/Dartmouth is in a state of transition from one of Canada's major ports to the land based headquarters of offshore oil developments for Nova Scotia. At the northern edge of the Shubenacadie River headwater lakes basin, Halifax International Airport has been expanded and it is expected to experience continuous increases in traffic over the next decade.

The four-lane Bicentennial Highway is the major artery connecting the city with the airport, and crosses the upper Shubenacadie River headwater lakes basin on its western edge.

Already development of the upper Shubenacadie River basin is becoming controversial with industrial parks and related industries being proposed and being at times opposed by citizens on environmental grounds.

When urban and industrial expansion occurs in any small drainage basin, there is usually a need for a development plan and appropriate environmental controls to minimize potential problems such as eutrophication, shoreline development, excessive runoff and subsequent shoreline erosion and siltation. However, in the Shubenacadie River headwater lakes basin, there is in addition to these concerns an already well known problem which may become more

critical with further development. During a study carried out in 1977 it was found that bottom sediments from some of these lakes contained significant concentrations of mercury, arsenic and some other metals. Past gold mining and explosives manufacturing are known to have generated wastes contaminated with mercury and arsenic, and lake sediments have been enriched by years of erosion and leaching of waste piles.

In addition to these anthropogenically enhanced toxic metal sources, the basin is naturally a source of some of these same metals. The Shubenacadie River basin is extensively underlain by the Meguma Group which contains slates with interlayer mineralization. The arsenopyrites, pyrites and other minerals found in these rocks are natural sources of arsenic and other metals associated with gold deposits.

The mineralized Meguma slates are thinly covered by glacial deposits, mainly of local origin. Any development which removes this thin overburden and results in exposure and fracturing of mineralized bedrock can result in in acid drainage with associated elevated levels of toxic metals, especially arsenic. In 1977, following construction activities at the Halifax International Airport, fish kills were reported in the Shubenacadie River due to acid drainage and/or elevated metal levels. Minor disturbances, for example digging of foundations, could cummulatively cause major acidity and metal increases in the lakes of the basin. In addition to these effects,

the basin lakes are also recipients of atmospheric acids. Thus, there are concerns that if buffering capacity and pH decreases in the Waverley area lakes by acidification, resolubilization of toxic metals from sediments will occur. Some studies on lakes acidification have also shown that an increase in acidity may be associated with an increase in mercury levels in fish populations.

Some cottage and house owners still draw their water directly from the rivers and lakes. There has already been evidence of arsenic poisoning related to groundwater/well water toxic metal concentrations. The Waverley area residents are therefore concerned that development will result in a variety of problems that will impair or impede their continued use and enjoyment of the lakes.

In late 1982, a joint federal-provincial study group was established to try to provide some answers to local concerns. The working group was composed of representatives from the Nova Scotia Department of Environment (J. Underwood, P. Schwartz), the Nova Scotia Department of Health (D. Feldman), the Environmental Protection Service (P. Eaton and L. Trip), the National Water Research Institute, Environment Canada (M. Mudroch) and was chaired by the Water Quality Branch - Atlantic Region, Environment Canada (T. Clair).

The objectives of a 1983-84 study that was proposed by the group were to evaluate the ecological sensitivity and trophic status of several Shubenacadie River headwater lakes; to quantify the transport of mercury and arsenic through the chain of the lakes

located in the vicinity of the past mining activities and to investigate the effects of the mine wastes on the water quality of the lakes. The study was designed to provide information for planners of urban and industrial development and to recommend appropriate environmental controls to minimize serious contamination of the Shubenacadie River system. The sampling plan for the study is shown in Appendix I.

This report is divided into a number of sections, each of which addresses various aspects of arsenic and mercury contamination in the Upper Shubenacadie River Basin. Recommendations for action and future work are based on the reported results.

INTRODUCTION

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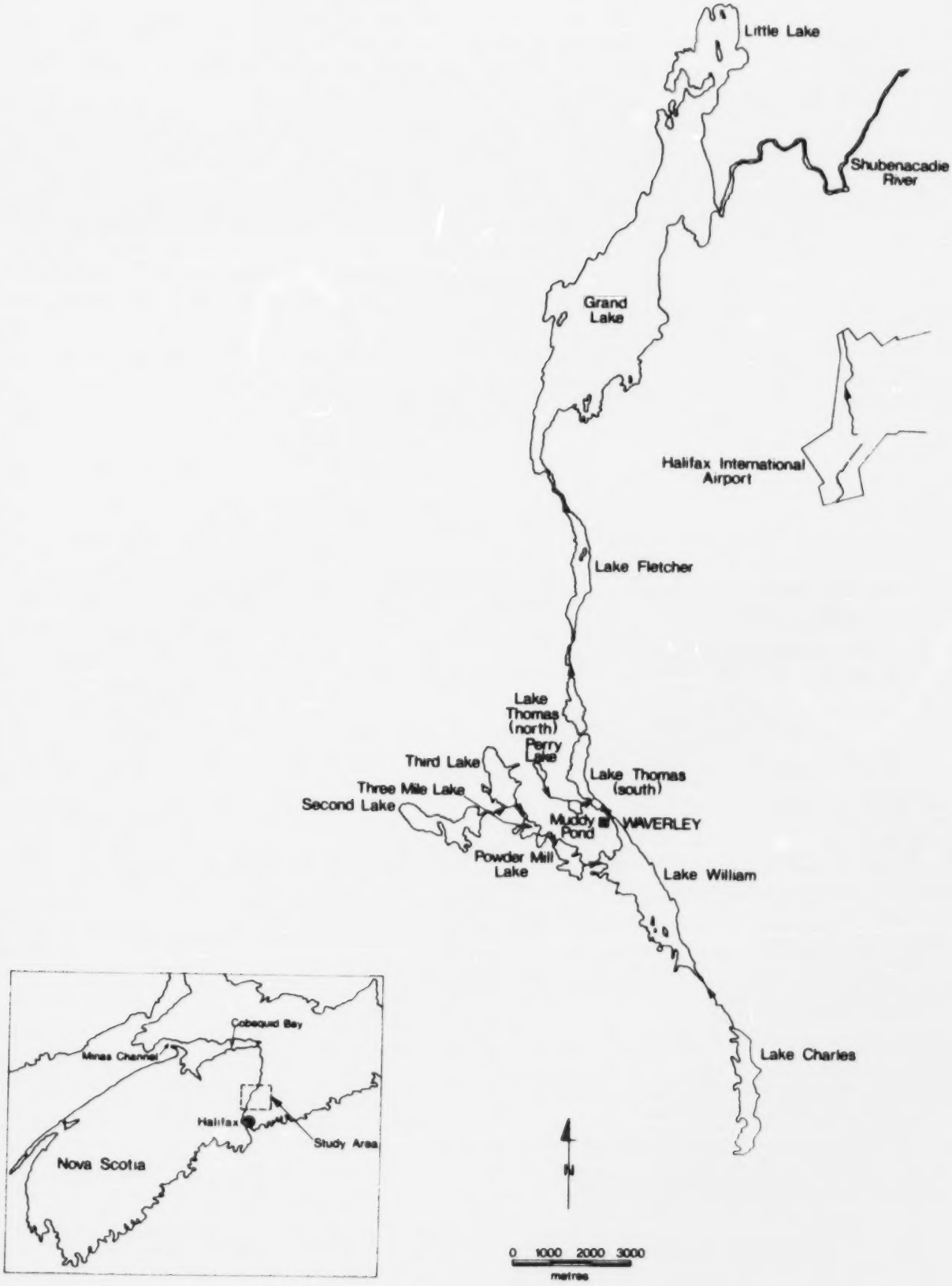
BASIN DESCRIPTION

The Shubenacadie Basin is the largest basin in Nova Scotia. It is approximately 110 km long and drains an area of 260 sq km. The river flows in a northerly direction bisecting the province with the river, flowing from Halifax and discharging into Cobequid Bay in Minas Basin. The largest tributary in the River Basin is the Stewiacke River.

The southern portion of the river system, more specifically the first 10 km, is referred to as the headwaters area. Within the headwaters there are approximately 110 lakes, ponds and bogs. Less than 12 percent of the total land area for the River Basin is found in the headwaters area.

The terrain in the area is composed of low hills and smooth topped ridges. The general trend of the contours and of the central chain of lakes, which include Charles, William, Thomas, Fletcher and Grand are in a north - south direction. This chain of lakes bisects the area creating a central valley and discharging through Grand Lake (Interprovincial Engineering Ltd., 1978) (Fig. 1).

A large portion of the area has slopes that exceed 5 to 10 percent and more than two-thirds of the shorelines the slopes are in excess of 20 percent (Interprovincial Engineering Ltd., 1978). With an increase in slope there is also, generally, an increase in the potential for erosion. The locations with high erosion potential are situated at or near the edge of lakes. Most lakes, except Rocky and


Little Lake
Shubenacadie River
Grand Lake
Halifax International Airport
Lake Fletcher
Lake Thomas (north)
Perry Lake
Third Lake
Three Mile Lake
Second Lake
Lake Thomas (south)
Muddy Pond
WAVERLEY
Powder Mill Lake
Lake William
Lake Charles
Cobequid Bay
Minas Channel
Halifax
Study Area
Nova Scotia
N
0 1000 2000 3000
metres

Soldier, have a moderate to high potential for erosion along their shores (Inland Waters Directorate, 1975).

The two most abundant soils in the area are the Halifax and Wolfville series. Other soil types include: Rockland, Gibraltar, Bridgewater, Peat, Mahone and Hantsport. The soils are unsatisfactory for agriculture due to limiting factors such as stoniness, shallowness, drainage and fertility. The soil series typical of this study area is also typical of the lake basins found within.

GEOLOGY

The study area is underlain by several rock types: Cambrian Goldenville and Ordovician Halifax Formations, Devonian granite, and various Pleistocene glacial deposits (Bujak and Donohoe, 1980). The Goldenville and Halifax formations are included in the Meguma Group which were originally deep sea sediments. Both formations were deposited as large volumes of sediment transported from the continental shelf of a landmass, which may have been North Africa, to the depositional area by fast flowing bottom currents (turbidity flows) (Bujak and Donohoe, 1980).

The Goldenville and Halifax formation consists of a siliceous basal part and a finer upper part, respectively (Roland, 1982). This group is a gold bearing series. The thickness of the two formations collectively is approximately 10 kilometers. The

Goldenville includes: greywacke, quartzite, gneiss and minor slate. Slate, schist and minor quartzite are found in the Halifax Formation.

Gold occurs in quartz veins which concentrate on the crest of anticlines or domes, along bedding planes, and in fissures in the slates and quartzites (Grantham and Jones, 1976). Minerals associated with these gold producing quartz veins are listed in Table 1, as well as their percentage of the vein by volume. The gold bearing veins are typified by greyish-white quartz or coarse grey slate with small cross veins of quartz (Mudroch and Sandilands, 1978). According to Newhouse (1936) a relationship exists between gold deposits and their proximity to the Devonian granite.

According to Interprovincial Engineering Ltd. (1978), surficial soil or overburden throughout the headwaters area consists mainly of glacial till with minor occurrences of alluvium and glaciofluvial sediments. The depth of the overburden is generally less than two meters (Mudroch and Sandilands, 1978). Though, along the eastern shorelines of William, Thomas and Fletcher Lakes the overburden is greater than five meters.

Table 2 gives the types and percent of soils found in some of the lake basins within the study area.

LAND USE

In 1791, Sir John Wentworth, governor of Nova Scotia, visualized a canal system along the Shubenacadie River, from Halifax

Table 1. Minerals Associated with Gold Bearing Quartz Veins.

(Graves, 1978)

Mineral	Percentage of Vein By Volume	Formula
Quartz	occasionally 50%	Si_2O_2
Carbonate	generally 5 to 10%	$CaCO_3$
Pyrite-arsenopyrite -pyrrhotite	a few	FeS_2-AsFeS-FeS
Gold	trace	Au
Chalcopyrite	trace	$CuFeS_2$
Galena	trace	PbS
Sphalerite	trace	ZnS
Feldspar	trace	$K\ SiO_4$
Rutile	trace	TiO_2
Scheelite	trace	$CaWO_4$

Table 2. Soil Series Characteristic of the Basins in the Headwaters Area (% of Basin) (Inland Waters Directorate, 1975)

Lakes	Wolfville	Halifax	Rockland	Hantsport
William	2	82	4	
Thomas	37	29		
Fletcher	58		28	
Powder Mill	10	90		
Third	44	30		

Lakes	Bridgewater	Mahone	Gibraltar	Peat
William				2
Thomas	35			
Fletcher	5	4	5	
Powder Mill				
Third	20			7

to Cobequid Bay. This was not a totally new idea, the Indians had used this water route in its natural state. In 1826, the first sod was turned for the canal's construction and 35 years later it was opened. There were 15 locks within the canal system. It operated for eight years until fixed bridges, for the railway, brought the canal system to an end. Lock numbers 10 and 11 are found within the study area. Lock number 10 was between Thomas and Fletcher Lake; and, lock number 11 was between Fletcher and Grand Lake.

Residential development is centered around the lakes and as a result construction could have a strong impact on water quality. Construction creates erosion and sedimentation problems and may contaminate the lake water with bacteria and viruses; reducing the lakes' ability to support recreational activity and more importantly affecting a possible water supply (Shubenacadie - Stewiacke River Basin Board, 1977).

Wastewater disposal is a concern in the headwaters area. Septic tanks are the primary method of disposal with a few small sewage treatment plants for various institutions, subdivisions and trailer courts. In future, residents of Fall River, Waverley, Fletcher, Wellington, Windsor Junction and Beaverbank will acquire central sewage systems (Shubenacadie - Stewiacke River Basin Board, 1981).

The area is serviced by individual surface and groundwater supplies, and a limited water system located on Third Lake (Nova

Scotia Environmental Control Council, 1982. The Village of Waverley will be serviced by water, piped from the Pockwock system, but no extension of this service to other communities is planned (Nova Scotia Environmental Control Council, 1982).

The Waverley Gold District was discovered in the fall of 1861 and was in production until 1937. It crushed approximately 168,098 tons of rock and recovered 73,105 ounces of gold, making a profit of approximately 1.5 million dollars (Montreal Engineering Ltd., 1978). As a result of mining, two toxic elements, arsenic and mercury have been introduced in relatively high concentrations, to the lake system. In 1976, it was discovered that a resident in Waverley had contracted arsenic poisoning from his own well water (Project Planning Consultants Ltd., 1979). Tailings and wasterock material, from this old gold area, have been blamed for the high concentrations of arsenic and mercury in the nearby water systems. These materials have been used in construction; and, because of their possible adverse effects on water quality, are now being monitored by the Nova Scotia Department of Environment (Shubenacadie-Stewiacke River Basin Board, 1981).

Acadia Powder Mill Company existed at one point in Waverley's history, between Powder Mill and Rocky Lake. This company dealt in explosives and as a result may have contributed to the high concentration of mercury in the surrounding lakes, particularly Powder Mill Lake.

More recently, the construction of the Halifax International Airport, in 1960, created acid waters which caused a large fish kill. The Grand Lake Fish Culture Station Hatchery closed in 1968 apparently as a result of the airport construction (Inland Waters Directorate, 1975). However, it is appropriate to note that no acidity problems have been associated with bedrock of the study area.

Presently, the largest mining operations are associated with the production of crushed stone. Gravel pits and rock quarries vary in size and they supply their product to locations in and around the Halifax-Dartmouth area.

There are approximately 80 wetlands in the headwaters and most of these areas are less than 20 hectares in size. Less than 1 percent of the total Shubenacadie-Stewiacke River Basin is devoted to agriculture, which all occurs in the headwaters area. In future, agricultural demands will probably not have a significant effect on water resources because of poor soils and increase in urban pressure. (Shubenacadie-Stewiacke River Basin Board, 1981). Approximately 15 percent of the total forest cover in the Basin is found in the headwaters area, with 90 percent of the headwaters area under forest cover. In future, forestry will probably be minimal, due to an increase in urban pressure (Shubenacadie-Stewiacke River Basin Board, 1981).

Recreationally, the headwaters area is very active. Several swimming areas are found around each lake. Other activities include various boating sports and fishing. Additional development might include hiking and bicycle trails that could be used as cross-country ski trails in the winter. Restoration of the Shubenacadie Canal was started in October of 1983, and will initially include Lake MicMac and Lake Charles. The restoration may include other headwater lakes in future years.

POPULATION

In 1976 the census figure showed that the headwaters area contained 50 percent of the total Basin population. Table 3 shows the population projections for the headwaters area. With a greater population, there will also be an increase in the threat to water quality and, therefore, there should be an environmentally stable plan for development of the area.

Table 3. Population Projections in the Headwaters Area

Population Projections	1976 Pop.	2001 Pop.	High Incr.	2001 Pop.	Low Incr.
Fall River/Waverley	1,939	13,696	11,757	8,127	6,188
Fletcher/Wellington	1,045	6,370	5,325	3,780	2,735
Windsor Junction	233	1,593	1,360	945	712
Rural (Waverley Area)	12,922	13,650	728	8,100	-4,822

(Shubenacadie-Stewiacke River Basin Board, 1981)

SOURCES OF ARSENIC AND MERCURY CONTAMINATION

There is a high probability of water contamination by arsenic where the residents obtain their water from groundwater travelling through mineralized slates and/or near an old gold mining site. Grantham and Jones (1976) show sources of arsenic contamination within wells; and, thus within the water system to be:

1) Tailings and Waste Rock: Several of the dug wells and some drilled wells studied are receiving groundwater from areas of tailings and waste rock deposits. The wells are high in arsenic and are similar in that they are receiving shallow groundwater

and sometimes surface water. In most cases leachate from tailings appear to be only a likely source of arsenic.

2) Abandoned Mine Workings: Some deep drilled wells in the mine workings are high in arsenic. At least one well in Waverley is reported to have penetrated a mine tunnel. The wells are similar in that they are receiving shallow groundwater or surface water and are likely receiving groundwater which has passed through an area of extensive underground workings.

3) Primary Geology: A small percentage of drilled wells studied away from the known gold area are contaminated with arsenic. In many cases excessive mineralization has not been observed in the area. There appears to be no other source of arsenic in these areas other than that disseminated in the bedrock.

4) Secondary Use of Waste Rock and Tailings: It has not been demonstrated that the use of waste rock or tailings in road construction, well construction, or other purposes is causing arsenic contamination of any of the wells studied. Some dug wells which are high in arsenic have been walled with rocks containing visible arsenopyrite. However, it is likely that some dug wells low in arsenic have been similarly walled.

Mercury contamination within the sediments may be attributed to a fulminated mercury explosive plant which was once located between Powder Mill and Rocky Lakes. Wilson and Travers (1977) mention possible sources for the high mercury levels as:

1) The use of mercury in the gold amalgamation process and the possible losses due to mishandling and carelessness.

2) The sulphides of the host rock of the Meguma Group may have above background mercury levels. Natural weathering of these rocks may be sufficient to cause elevated mercury levels in various water courses. The presence of oxidizing pyrite would greatly promote the release of mercury from the sulphides.

PREVIOUS WORK ON THE METAL CONTAMINATION PROBLEM

In 1976 the Provincial Government appointed a task force known as Grantham and Jones Task Force to study the arsenic problem in the Waverley area (Riverlake Residents Association, 1981). The task force found high quantities of arsenic in bottom sediments of Lake William, Lake Thomas and Muddy Pond; and recommended that Muddy Pond be posted unsafe (Riverlake Residents Association, 1981).

Lake bottom sediments were studied in 1977 and results showed sediments from Muddy Pond, Powder Mill, William, Thomas and Fletcher Lakes contained high concentrations of arsenic and mercury (Mudroch and Sandilands, 1978).

Possible source of sediment contamination is probably the result of the dumping of mine tailings into Muddy Pond. In addition, elevated concentrations of metals and arsenic were found in the beach material at Powder Mill and Muddy Pond (Shubenacadie-Stewiacke River Basin Board, 1981).

PROJECT STUDY AREA

The area studied by the working group is shown in Figure 1. Table 4 lists the water bodies sampled and the communities situated nearby.

The water residence time in the major lakes is between 4 and 5 months; but may vary depending on hydrological conditions from less than a month to over a year (Table 5). During the summer months these lakes have elevated fecal coliforms and are thermally stratified (Shubenacadie-Stewiacke River Board, 1981).

Two major tributaries found in the study area are the Fall River System and the Powder Mill Lake System. Figure 1 illustrates the flow patterns of the two major tributaries and the small Perry Lake-Muddy Pond tributary.

Table 4. Communities and Lakes in the Study Area

Communities	Lakes/Ponds
Fall River	Fletcher
Waverley	Muddy Pond
Wellington	Perry
Windsor Junction	Powder Mill
	Third
	Thomas
	Three Mile

Table 5. Summary of Physical Characteristics for Five Lakes in the Shubenacadie Headwaters Study Area*

Lakes	Fletcher	Thomas	William	Third	Powder Mill
Elevation (m)					
Above M.S.IL.	16.2	18.6	19.5	31.1	30.5
Shoreline (km)					
Length	6.9	9.2	12.7	5.2	3.2
Drainage area (ha)					
Total	14330.0	12792.2	7624.3	1064.3	2664.9
Local	1537.8	704.2	3095.9	372.3	293.4
Surface area (ha)	105.0	113.0	305.0	83.0	42.0
Depth (m)					
Mean	4.8	4.0	10.3	6.6	4.3
Max.	10.1	12.2	28.3	24.4	13.4
Flushing Time (months)					
Mean	0.3	0.5	5.4	6.9	0.9
Min.	0.4	0.5	5.9	8.6	1.1

*Data from Inland Waters Directorate, Atlantic Region.

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A HISTORICAL OVERVIEW OF THE WAVERLEY AND MONTAGUE GOLD MINE OPERATIONS ON THE SHUBENACADIE HEADWATER SYSTEM, NOVA SCOTIA

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INTRODUCTION

The purpose of this section of the report is to locate and map abandoned gold mines and tailings disposal sites in the Shubenacadie Headwaters Study Area. Any land management and planning exercise should incorporate this knowledge to avoid unnecessary disturbance of such sites which could result in accelerated release of the contaminants associated with the sites (i.e. arsenic, cyanide, mercury).

Most gold mining activities in Nova Scotia relied heavily on the mercury amalgamation and, later, cyanidation processes for the extraction of gold from ores.

An article by Gesner (1863) describes the process of gold extraction used at the time of the first discoveries in Waverley:

> "Gold dissolves speedily in mercury, at ordinary temperatures and the Spaniards were probably the first to adopt the process of amalgamation, which is the cheapest mode of operation upon large quantities of material. The Mexicans grind the auriferous rocks and mercury together in crude stone basins, surmounted by heavy rollers, and the Spanish raster, so called, is still in use. The amalgam, when formed, is collected over into a receiver, and the gold remaining in nearly a pure state in the retort. But in order to obtain an amalgam it is necessary that the gold and mercury should be brought together in absolute contact,

> and therefore it is important that the rock should be finely powdered, before the mercury is applied. For this object, various kinds of crushers have been invented, and of them, none have been found more useful than the common stamper, now in general use. (Several kinds of crushers and amalgamators were exhibited, with a variety of gold ores from Foreign Countries, and a beautiful wreath of the gold of Nova Scotia.) To extract every particle of gold from quartz by amalgamation, is a very difficult operation, and one that requires time and much experience; yet like all other inventions which have not been brought to perfection, almost every miner professes to have a knowledge of the art. Already have a number of the schemes introduced into Nova Scotia to remove the gold from its gauge failed, and some of them have been relied upon without any knowledge of mechanics, chemistry, or the properties of matter. In California and Australia, companies have been successful in obtaining gold, by following those who had first crushed the rock, or cradled the sand, and from the tailings of the first adventurers, fortunes have been won."

As well, a prophecy of the riches to come, in the eloquence of the day, was made in the closing paragraph of the same article.

> "I have no doubt the time will arrive when the various interests of many parties now engaged in gold mining in Nova Scotia, will be more or less united, and the work of extraction will be successfully performed. In the meantime, the gold-seekers will extend the present discoveries, - men and machinery will come in and prevent the abandonment of other useful pursuits and branches of industry, such as agriculture and the fisheries, - and finally, by the united efforts of all, under a wise and harmonious government, the Province will lift up her head and shine as one of the brightest gems of the British Empire."

Mining activities involved the construction of underground workings and the transport of mineralized rock to the surface. Mine waste (waste rock or black rock) was discarded and spread around mining communities. Such rock was often used for road, railway and well construction. Mill tailings were generally washed downslope from the stamp mills, often finding their way into lakes, rivers and swamps. A calculation of the average of the arsenic values reported in 1921 (Province of Nova Scotia, 1921) showed that the tailings contain 0.4% arsenic.

Today, the remains of past mining activities are recognized as a primary source of arsenic, cyanide and mercury contamination. Leachate from exposed bedrock, mine waste dumps and mill tailing dumps have led to environmental problems such as contamination of groundwater and lake sediments. Various tailing locations were sampled in the Waverley/Montague area to gain insight into the present concentrations of these contaminants (arsenic, cyanide, mercury) and results are reported here. Underground mine workings provide channels of least resistance for groundwater flow, frequently in a direction other than that predicted by hydrogeological assessment. The locations of old mine sites are thus also shown in this report.

Information presented in this report has been derived from technical journal articles obtained from the Technical University of Nova Scotia (Department of Mines), the Environment Canada Library and the Dalhousie University Library, personal communication with members of the Nova Scotia Department of Mines, Department of Environment, Department of Health and Department of Lands and Forests, and regional

Environmental Protection Service offices. Some information regarding the location of tailings ponds and waste rock dumps was obtained from a private citizen in Waverley who researched this area. Most of these sites were confirmed from maps at the Nova Scotia Department of Mines, field trips and from a residing geologist in Waverley who was a member of the Arsenic Task Force studying arsenic poisoning in Waverley.

HISTORY

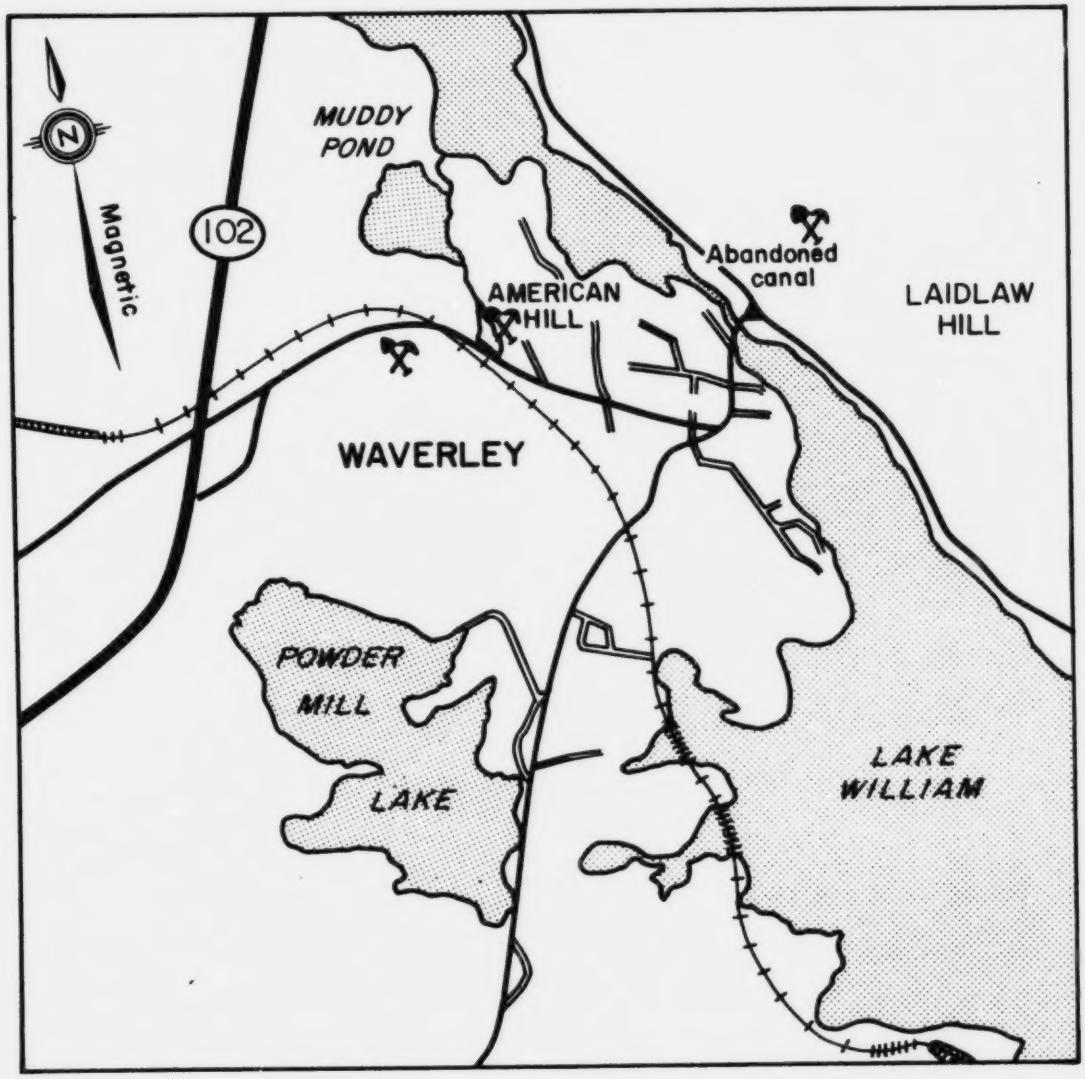
Waverley Gold Mine Operations

The village of Waverley (Figure 1), 18 km north of downtown Halifax, owes its existence to the discovery of gold. Waverley's gold era was from 1861-1937; and a recorded 73,105 oz of gold were extracted from 168,098 tons of ore crushed (Montreal Engineering Company Limited, 1978).

Gold in Waverley was discovered by Alexander Taylor on August 31, 1861, on the edge of Muddy Pond on the Waverley Farm, also known as the Allen Farm. The Chebucto Mining Association, a group of Halifax merchants, was incorporated to perform a thorough prospecting of the farm. They obtained the exclusive rights to search until May 1, 1862.

Although this farm included all of what is now West Waverley, the Chebucto Mining Association was unsuccessful in

FIGURE I. WAVERLY GOLD DISTRICT



discovering any lodes sufficiently auriferous to warrant mining of any large area. On May 1, 1862, however, Alexander Taylor exposed an auriferous vein at the place where he had discovered the boulders the preceding year. As a result, several leads were opened by the Wolfville Company and Nova Scotia Gold Company between Muddy Pond and Lake Thomas.

The discovery of gold in East Waverley was made by James Skerry on Laidlaw Hill on September 14, 1861. During the next three years, the Waverley Gold District steadily increased production. By 1864, the output of this district greatly exceeded that of any other district in Nova Scotia.

The Waverley gold boom continued into the mid-1860s, but by 1868 production lessened and Waverley lost the distinction of ranking first among the gold districts of the province. This trend continued through the 1880s. Tailings were treated to extract remaining gold during this latter decade, but with little success.

Production increased in 1890; the West Waverley Gold Company erected a ten stamp ore crushing mill in 1892 to which ten more stamps were added in 1893. Operations continued under the Tudor Gold Mining Company in 1894. Considerable profits were made until the gold industry hit another slump in 1897.

Production increased again in 1901, when a cyanide plant was erected by Sydney Smith. After treating 2000 tons of tailings it was shut down since not enough gold was extracted to make it profitable.

From 1904 to the last year of major operation in 1937, production continued on a moderately low scale.

Montague Gold Mine Operations

In the early 1860s, the discovery of a boulder weighing less than 100 pounds and yielding $1600.00 in gold initiated careful prospecting in the Montague area. Soon after, other gold-bearing boulders were found in the area and active mining commenced in 1863.

Production increased throughout 1864-1865, and in 1865 a crusher was erected (all ore mined prior to the construction of this crusher was milled at Waverley). From 1866-1869 production lessened, largely due to insufficient machinery. This trend reversed in 1870 and the Albion (or McQuarrie) Mine was reopened. In 1873, a ten stamp mill was erected and 10,000 oz of gold were extracted from the Albion Mine from 1870-1874.

Work on the Albion Mine ceased in 1874 and production in the Montague area continued on a small scale from 1874-1878. After this stagnation period, production increased with the discovery of an auriferous lead (Rose Lead) on December 7, 1878. Large yields were obtained until 1880 when the miners ran into water problems. Small profits were obtained until the close of the Rose Lead in 1882. Production remained on a small scale until 1885.

Montague recorded its highest profits ever in 1885, but yield dropped again in 1886-1888. In 1889, profits increased

substantially and continued until 1899. Thereafter, the yearly yield was moderately low (with the exception of 1916-1917 which reported good returns). This trend continued until the last year of major operation (about 1939). A recorded 68,139 oz of gold were recovered from 134,278 tons of ore crushed.

This operation generated a large tailings delta was generated which consequently extended in a westerly direction through the swamps and streams making up Mitchells Brook. This brook empties into Lake Charles which is connected by streams south into Halifax Harbour and north into the Shubenacadie Headwaters lakes. Sand and slimes from this operation are easily visible in the swamps, an area of about 13 hectares. The 1921 Annual Report on the Mines, Department of Public Works and Mines, Province of Nova Scotia, states that, "The depth (of tailings) as a rule does not exceed five feet."

MINING BY-PRODUCTS

The waste generated from earlier gold mining activities was generally divided into two categories: mine waste and mill tailings. The recorded tonnage of ore milled at Waverley and Montague (168,098 tons and 134,278 tons, respectively) is indicative of the quantity of wastes (either in the form of mine waste or mill tailings) present within each gold district.

Mine Waste

Mine waste included black rock (Meguma shales), which was mined along with the gold-bearing quartz veins and contained little gold, and other waste rock that was considered too low grade to warrant crushing. Both types of rock were sent to the rock dumps.

In the early days, only high grade rock was sent to the mills for crushing. The remaining mine rock was classified as mine waste and sent to the rock dumps. Consequently, gold in concentrations as high as 24 g per tonne of waste rock was lost to these dump sites (Province of Nova Scotia, 1921).

The rock dumps at Waverley are large and numerous and can be seen on American Hill, throughout Laidlaw Hill and adjacent to Muddy Pond. In addition, smaller rock piles were noted to surround the mouth of almost every shaft.

Mill Tailings

Mill tailings consists of slimes and mine sand generated in the mills after crushing and processing auriferous ore it to extract its gold content (i.e., mercury amalgamation and cyanidation).

Mills were often located on hills and the mill tailings released into a sluice, run down the side of the hill and formed a tailings pond. Coarse sand remained on the slope and the fines or "slimes" ran into the swamp. This is the case with the Muddy Pond

area - mine tailings can be seen on the banks of this swampy area and beneath the surface of the water. In some cases these tailings ponds became so high that further tailings were required to be hoisted up in buckets and dumped over the tailings mound. Often, lakes and streams became convenient disposal sites for mill tailings, for example Lakes Thomas, William and Powder Mill.

The tailings dumps were generally "fan-shaped" grading into a swamp. Sediments in Powder Mill Lake were found to contain elevated concentrations of arsenic (800 ppm), mercury (45 ppm) and lead (300 ppm). Lakes William, Thomas and Fletcher also have elevated concentrations of these elements, but not to the same degree as Powder Mill Lake (Shubenacadie-Stewiake River Basin Board, 1977).

One possible explanation for the high concentrations of contaminants reported in Powder Mill Lake is that, in addition to past gold mining activities, this lake may also have served as a disposal site for the Acadia Powder Mill Company operating in 1862-1913. This company manufactured black powder. Certain detonators such as mercury or silver fulminates may have been used and such wastes discarded.

IDENTIFICATION OF MINE AND TAILING SITES IN WAVERLEY AND MONTAGUE

The locations of abandoned gold mines, mill tailings and waste rock dumps from the districts of Waverley and Montague which have been identified are shown in Figures 2 and 3, respectively.

FIGURE 2. WAVERLY AREA DESIGNATED SITES

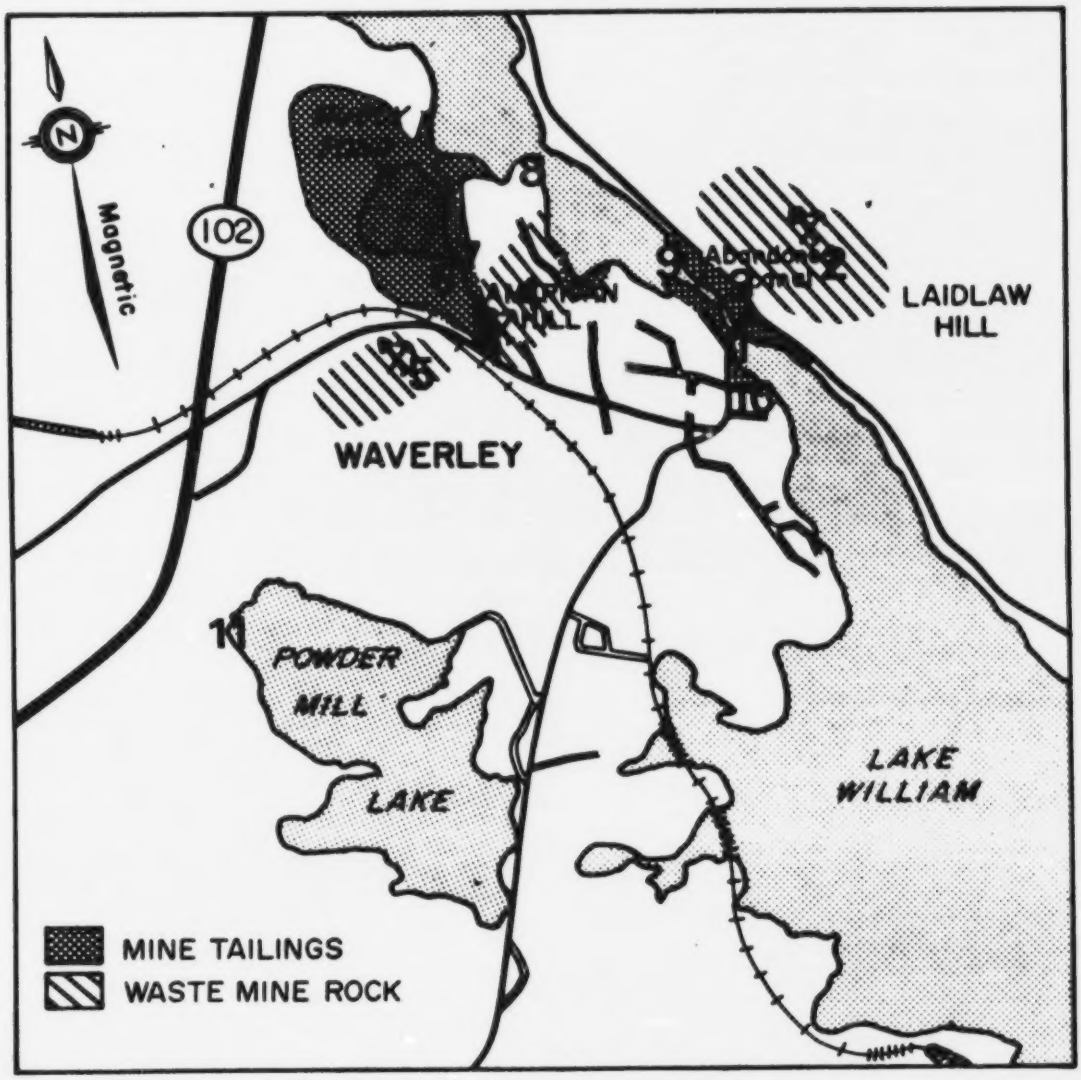
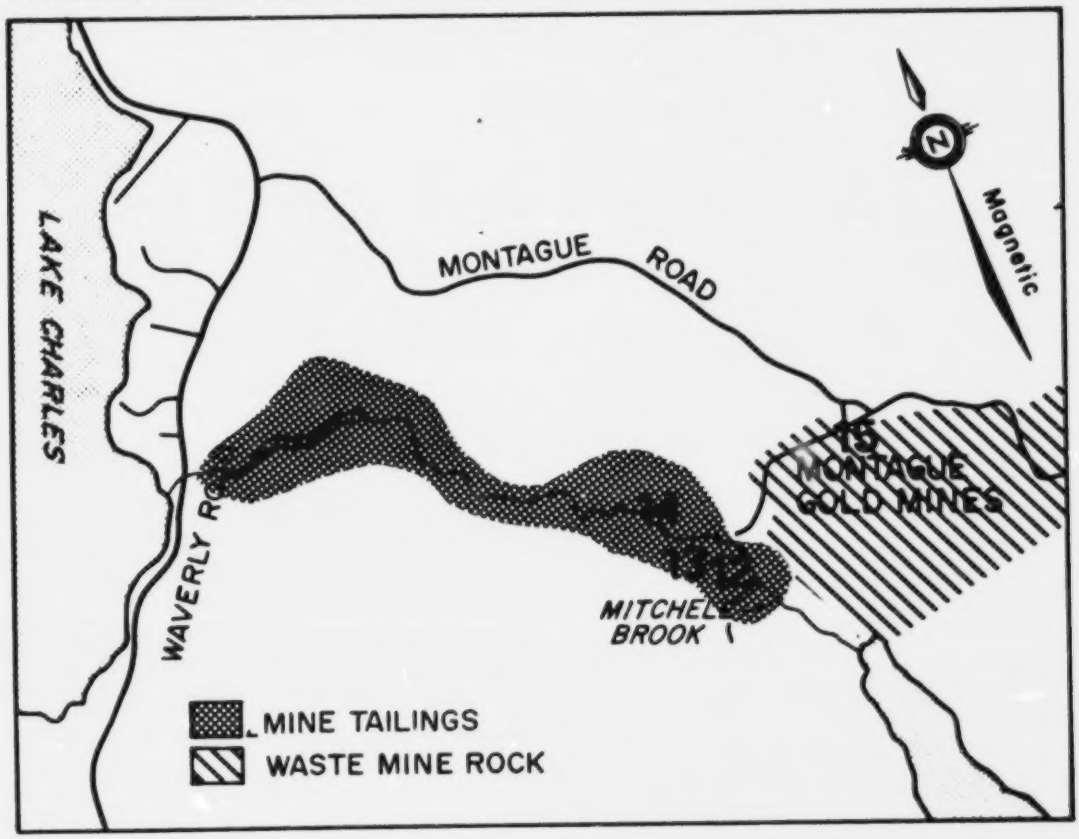


FIGURE 3. MONTAGUE MINES DESIGNATED SITES



These areas have been extensively mined: Lakes William, Thomas, Powder Mill and Muddy Pond have served as convenient disposal sites for mine waste generated from numerous mining companies. The shores and sediments of these lakes are now highly contaminated with arsenic, mercury and possibly cyanide.

Site 1 - This site served as a dump for mill tailings (sand). A store was located adjacent to and directly across the road from this tailings flat. Today, an Irving Oil Service Station operates on the tailings flat.

Site 2 - This area is part of Laidlaw Hill and is located approximately .5 km north of the Irving Station. Waste rock can be seen throughout the area which is now heavily wooded. An old cement foundation remains, this may have been the water power house, as shown on the Faribault map, adjacent to the road. Today, a few houses are built on this site and large areas of waste rock are still present.

Site 3 - According to the 1901 Faribault map, this site (located at the outlet of Lake William) was the site for a stamp mill. This mill may have belonged to the Waverley Gold Mining Company which was reported in a June, 1893 paper to have obtained permission to dump mine waste into the mouth of the canal. Today, an ice cream store and automotive repair shop occupy the area.

Site 4 - This is the American Hill area. The bank adjacent to Muddy Pond is moderately wooded: waste rock and quartz are scattered throughout. A few houses are built on this hill.

Site 5 - According to Faribault's 1901 map, this was the location of a 10 stamp crusher. One corner of its concrete frame still remains. Presently, this area is a large waste rock dump, the surrounding area being heavily wooded.

Site 6 - This is the site of a now insolvent plastics fabricating plant known as LeGays Plastics.

Site 7 - Muddy Pond is a swampy area adjacent to waste rock (on the American Hill side) and has large visible quantities of mine sand on its banks. It was reported in one newspaper in June, 1983 that mine tailings dumped into this pond by the West Waverley Gold Company was so vast that it raised the water level of the pond, causing the Lake View Mine to flood. After a process of litigation, it was agreed that the Waverley Company could dump its wastes along the shores of Lake Thomas and to use Muddy Ponds "for any purpose whatsoever" (Hartlen, 1982).

Site 8 - This site is a tailings flat that extends into the water and onto the shore of the western side of Lake Thomas.

Site 9 - Tailings sand extends along the eastern shore of Lake Thomas from the mouth of Lakes Thomas and William, approximately 350 up the shores of Lake Thomas.

Site 10 - This is a sand tailings site which borders the western side of Lake William.

Site 11 - This site is a large tailing sand area extending from the mouth of Powder Mill Lake flowing towards Three Mile Lake. Furthermore, information obtained from maps from the Nova Scotia

Department of Mines indicates that small quantities of waste rock can be found around each mine shaft.

Sites 12, 13 and 14 are large swamp areas located in the Montague Mines area. There are large quantities of visible mine sand throughout these areas. These areas are surrounded by a mature forest.

Site 15 is a mine waste area with large quantities of waste rock visible throughout. Underground workings can be traced through the series of mounds of waste rock on the surface aligned in an east/west direction.

Site 16 is the Lake Charles area. Of particular interest is the layer of mine sediment (slimes) found during the sampling exercise for this report. The depth of material is unknown since the corer used was unable to penetrate the "slimes" horizon and intersect the organic layer that must have been present prior to the mining activity.

EFFECTS OF PAST GOLD MINING ACTIVITIES

The most commonly used method to extract gold from ores was mercury amalgamation and, later, cyanidation. A description of both processes is found in Appendix II.

Firstly, the methods and practices of earlier gold mining were crude and wasteful. This was largely due to the fact that the

miners and mine managers were generally men of little or no experience in the art of mining. Consequently, relatively high concentrations of mercury and cyanide were allowed to escape with the tailings.

Most of the gold in this area was free milling, recoverable by amalgamation. Complex ores containing metallic sulphide minerals could not be treated by this process. Inexperienced miners were content with the amount of gold obtained by free milling and did not concern themselves with the more difficult metallurgical problems associated with gold extraction from sulphide ores. Consequently, much of the gold was lost in the tailings.

Attempts in the 1880s to treat tailings and sulphide ores to extract remaining gold met with little success. These early failures adversely affected the mining industry and led to the belief that gold not recoverable by free milling was not worth trying to save. Again, tailings became labelled as waste and were discarded into swamps and lakes.

Gold deposits in this area are almost entirely located in the rocks of the Meguma series originating in the lower Ordovician period and are composed of slates interspersed with quartz dikes. This rock is host to a number of minerals including arsenic, gold and mercury being among them.

Mine waste (waste rock) from underground mining activities was brought to the surface and distributed throughout the community. Often this rock was used in the construction of well walls, roads and railway beds. The exposure of this rock to acidic weathering

conditions resulted in the release of arsenic and mercury into surrounding soils, raising the concentrations of these metals in the environment.

The movement of acid mine drainage through abandoned shafts provides a means of mobilization for these metals as they dissolve into the solution. These metals can thus be transported via groundwater into wells and lakes. The direction of groundwater flow may not follow predicted hydrogeological patterns, since up until the early 1900s no records or plans of underground workings were kept and much valuable information was lost. To date, the locations of these underground shafts and the direction they follow remains generally unknown.

No regulations governing disposal operation of mill tailings existed at the time of mining. Consequently, nearby lakes, ponds, streams and depressions served as convenient disposal sites for contaminated tailings. Newspapers dating back to 1893 reported large quantities of tailings being continually dumped into Muddy Pond and Lakes William and Thomas. An exerpt from the Annual Report on the Mines, Province of Nova Scotia, 1921 (Table 1) shows this lack of concern for the receiving environment in the "Remarks" column.

These factors have resulted in the problems facing the Shubenacadie Headwaters Area. To illustrate the potential for impact, several sites were analyzed for the contaminants in question and the results are presented in Table 2 and sampling locations are given in Figures 2 and 3.

Table 1. Samples and Assays of Old Tailing Dumps

Locality	No. of Samples	Gold ozs.	Silver ozs.	Arsenic ozs.	Approx. Tonnage	Remarks
Waverley, Taylor-Hardman, 1 and 2	2	0.01	trace	trace	unknown	-
Waverley, Taylor-Hardman, 3 and 4	2	0.025	0.005	0.89	50,000	-
Waverley, Taylor-Hardman, 5	1	0.025	0.005	0.93	unknown	All in lake
Waverley, Gold Mining Co.	1	0.01	0.003	trace	unknown	-
Waverley, American Dump	2	0.028	0.004	0.54	10,000	-
Waverley, Wilson's	2	0.02	0.001	0.34	1,000	-

Table 2. Concentration of Contaminants at Several Sites

	Location Waverley Mines	Parameters		
		Arsenic $_{\mu g \cdot g^{-1}}$ (As)	Mercury $_{\mu g \cdot g^{-1}}$ (Hg)	Cyanide $_{\mu g \cdot g^{-1}}$ (CN^-)
1	Laidlaw Hill	3908	0.07	<0.30
2	Lake Thomas	272	0.07	0.62
3	Muddy Pond	6196	6.21	0.37
4	Muddy Pond Waste Rock	467	0.35	<0.30
5	American Hill at Muddy Pond	3863	1.75	50.70
6	Powder Mill Canal to Rocky Lake	7939	2.19	<0.30
7	Muddy Pond (North)	5910	0.09	<0.30
8	Muddy Pond (South	3806	0.11	1.54
9	Lake Thomas (Mouth)	694	0.11	.51

Table 3. Concentration of Contaminants at Montague Mines and in Lake Charles Sediment

Location Montague Mines	Parameters		
	Arsenic $_{-1}$(As) $\mu g \cdot g^{-1}$	Mercury $_{-1}$(Hg) $\mu g \cdot g^{-1}$	Cyanide $_{-1}$(Cn-) $\mu g \cdot g^{-1}$
Montague Mines			
Tailings Delta			
1) Sample #1 (surface)	9348	1.30	1.60
2) Sample #2 (surface)	13673	3.60	4.50
3) Sample #3 (.5 m depth)	911	0.30	.30
4) Sample #4 (.5 m)	9750	0.10	4.70
Lake Charles			
5) Mitchells Brook	580	1.00	11.5
6) Core #1 slimes	86	<0.03	-
organic	134	0.20	-
) Core #2 slimes	106	<0.03	
organic	no sample		
8) Core #3 slimes	55	.10	
organic	195	.30	
9) Core #4 slimes	103	<0.03	
organic	203	0.30	

Lake Charles was investigated by core sampling and a very solid layer of apparent mine slime was encountered about 20-80 cm below the organic layer now covering the lake bottom. An analysis of the core samples as well as analysis of the tailings delta material was conducted for contaminants. The results are shown in Table 3 and sampling locations in Figure 3.

SUMMARY

The gold mining activity around the Waverley/Montague area commenced in 1861 and lasted until 1939. Gold mine operations generated 168,098 and 134,278 tons of mine waste and mill tailings, respectively. Nearby lakes, streams, ponds and depressions served as disposal sites for these wastes, resulting in the contamination of these areas.

Tailings sites, mine waste dumps and abandoned mine shafts, considered to be the primary sources of arsenic, cyanide and mercury contamination, are shown on maps accompanying this report. A general description of these sites is also included.

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SURFACE WATER QUALITY OF THE SHUBENACADIE STUDY LAKES AND INTER-CONNECTING STREAMS

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INTRODUCTION

The study area is located in a semi-urbanized environment, where low density housing and some light industry are clustered around the lake shores. The study lakes are located within 10 km of the Halifax-Dartmouth urban area and are bordered by secondary and major highways, so are potentially affected by a number of anthropogenic influences which have nothing to do with old mining sites.

Surface water quality in the study area is one of the factors most likely to be of immediate interest to residents and developers, due to its use for drinking. The purpose of this study was to assess the present state of surface water quality in the Waverly area, to compare it with various use standards and to values reported in the past. These data can then be used in assessing the impact of land-uses and sediment quality which are discussed elsewhere in this report.

This study was conducted jointly by the Nova Scotia Department of the Environment, which did the sampling, and the Inland Waters Directorate of Environment Canada, which was responsible for sample and data analyses.

AREA

The sites sampled included seven lakes and five interconnecting streams. These, along with their sampling frequencies are

shown in Table 1. In order to aid in the interpretation of the data, the lakes and streams have been placed into two groups based on drainage systems. The first (System A) is composed of Third Lake, which drains into Three Mile Lake, draining into Powder Mill Lake. Powder Mill empties into Lake William, which goes into Lake Thomas and then to Fletcher Lake. This drainage is approximately 106 km^2 in area. System B is much smaller, and is made up of Perry Lake which drains into Muddy Pond, which goes into Lake Thomas. This series of lakes covers a 2.5 km^2 area. All lake water samples were taken at the deepest points of the lakes, except for Perry Lake, which was sampled from the shore due to the difficulty in bringing a boat to the site.

METHODS

Field

Sampling for major ions and metals was done by the Nova Scotia Department of the Environment four times over the study period. Sampling of connecting streams was done from the stream banks, while the lakes were sampled using a 2 litre Van Dorn sampler. The sampling depths chosen were based on the lakes' thermal profiles, with a sample being taken in the epilimnion, one in the thermocline and another in the hypolimnion, 1.5 m from the surface. In some cases, where the thermal profile was complex, extra samples were taken for better water quality coverage. In April and November, when lakes

Table 1. Sites Sampled, Depth at Lake Sites and Sampling Dates for Major Ions and Metals in 1983

Site	Depth (m)	Sampling Dates
Str. L. Thomas to L. Fletcher	N/A	May 5, June 14, Aug 22, Nov 23 Feb 16
Str. Muddy Pd to L. Thomas	N/A	May 5, June 13, Aug 17, Nov 23 Feb 16
Str. L. William to L. Thomas	N/A	May 5, June 14, Aug 22, Nov 23 Feb 16
Str. L. Three Mile L. to Powder Mill L.	N/A	May 5, June 15, Aug 22, Nov 23 Feb 16
Str. Powder Mill L. to L. William	N/A	June 13, Aug 19, Nov 23, Feb 16
Powder Mill L.	13	Apr 26, June 14, Aug 18, Dec 1
Third L.	23	Apr 27, June 13, Aug 22, Dec 1
L. Thomas	13	May 5, June 14, Aug 22, Nov 23
L. Fletcher	8	Apr 26, June 13, Aug 22, Nov 22
Perry L.	N/A	May 5, June 15, Aug 16, Dec 1
Muddy Pd	1	Apr 27, June 14, Aug 23, Nov. 23

were isothermal, samples were taken one meter below the surface, midway through the column and one meter from the bottom. In shallow Perry Lake and Muddy Pond, only one sample was taken, 1 meter below the surface.

Field values were taken for water temperature and dissolved oxygen. Metal samples were preserved with concentrated nitric acid soon after collection. Metal blanks were also preserved for quality assurance at each sampling run. Based on the blanks, contamination from handling was noted at times in the study and the contaminated values deleted from the results.

Laboratory

All water samples were analyzed according to the Water Quality Branch Analytical Methods Manual (WQB 1979). Values recorded for sulfate were done using the ion chromatograph and all metal values were done using the MIBK solvent extraction technique, with an atomic absorption unit. All samples had to show major ion balance of 10% or better to be accepted. All data were transferred to Environment Canada's National Water Quality Data Bank (NAQUADAT). NAQUADAT station numbers and parameter codes are listed in the accompanying Tables.

RESULTS AND DISCUSSION

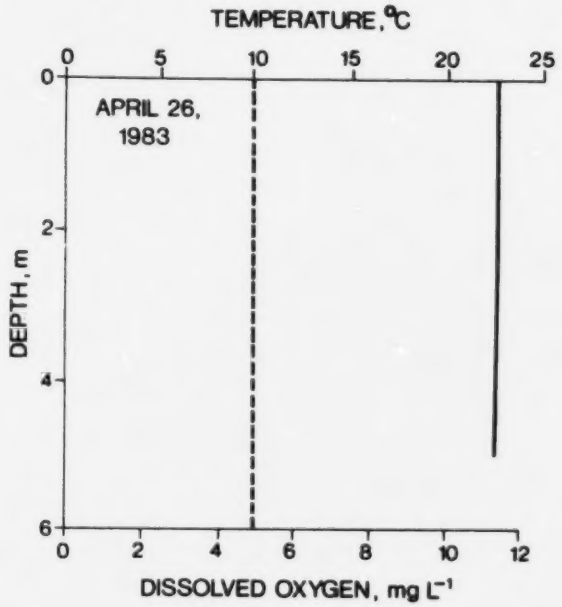
Lake Water Temperature and Dissolved Oxygen

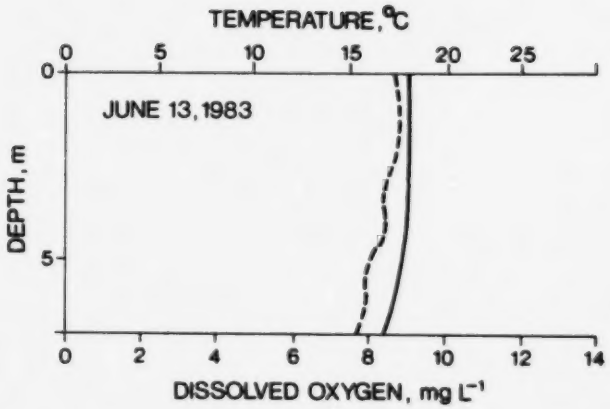
The lakes in the study area are typical for Nova Scotia. They are generally shallow and unprotected by mountains or cliffs, so are then subject to ambient winds and storms. This ensures that throughout much of the year, the lakes are well mixed, as is shown by the April and November-December isotherms (Fig. 1 to Fig. 6). The data show that during the study period, a weak stratification was set up in June and that, in August, strong thermoclines were set up between 6 and 10 meters depth in all lakes except Muddy Pond, which was too shallow, and Fletcher Lake. Why no stratification occurred in Fletcher Lake site may be due to three factors. First, the lake may be more exposed than the others to wind-driven mixing. Secondly, the flushing rate of the lake may be high enough to prevent the setting up of thermal stratification; and, thirdly, the sampling site might be located in an area subject to strong currents, which would also prevent stratification.

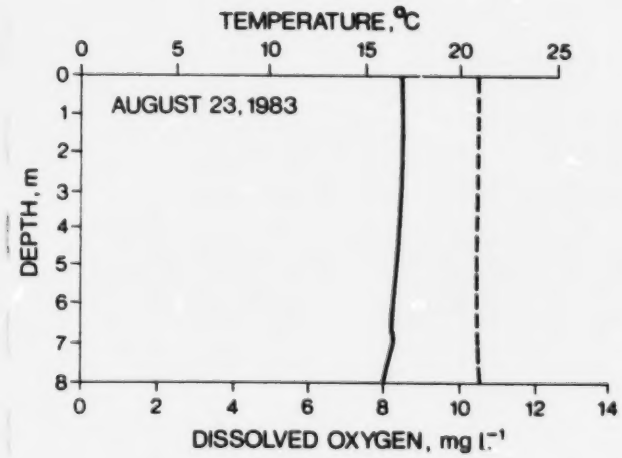
A short-coming of the study was caused by the dangerous ice conditions in February which did not allow temperature profiles or samples to be taken. We can probably assume that little stratification has occurred, as the ice cover was sporadic.

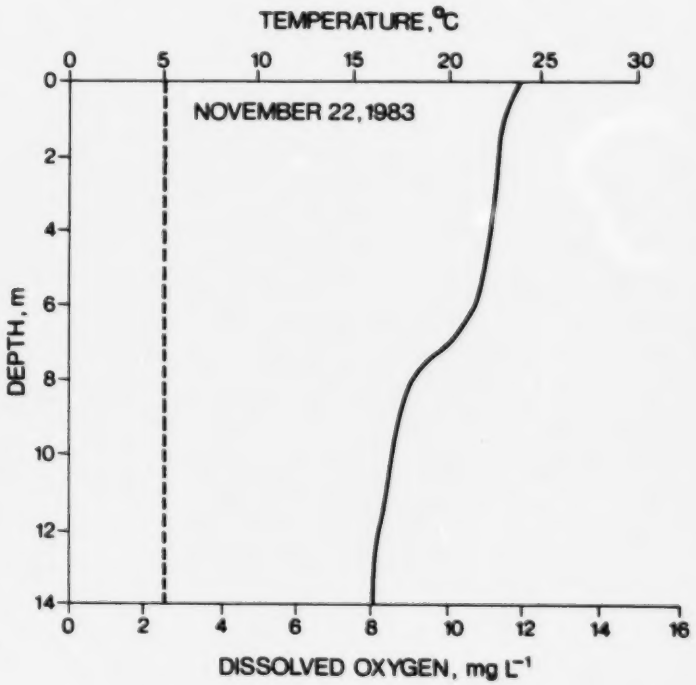
Dissolved oxygen (D.O.) levels at the lake sampling sites were closely affected by the trends in temperature. Dissolved oxygen

LAKE FLETCHER



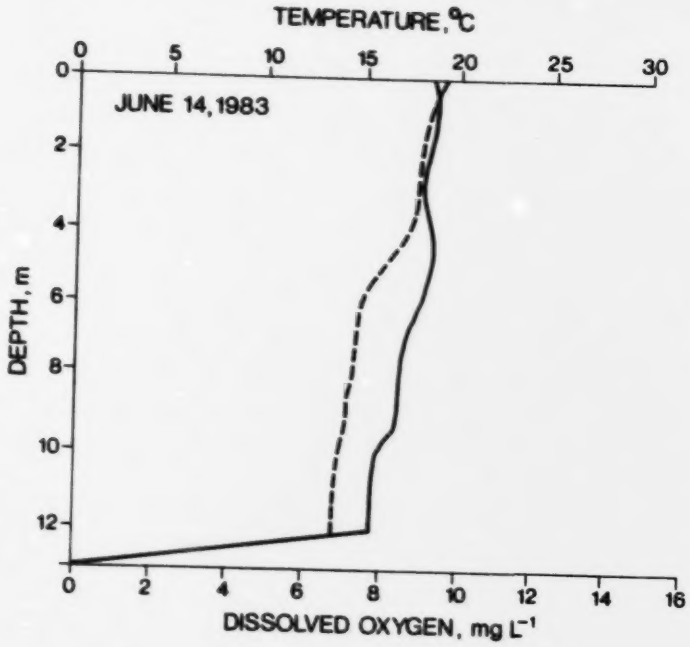


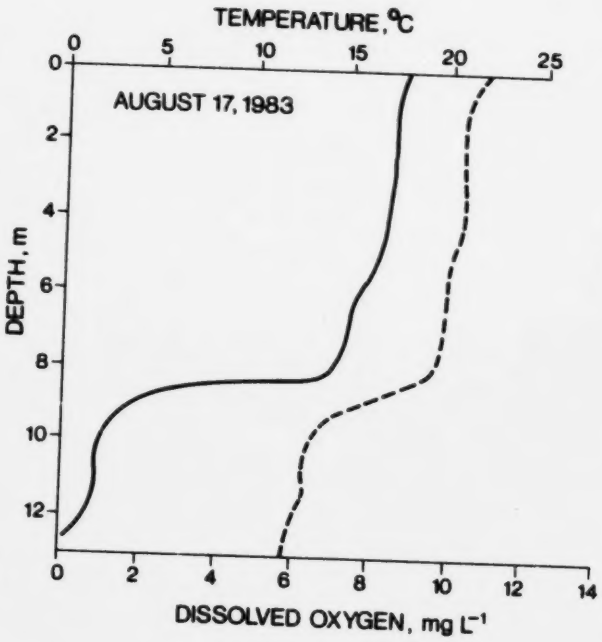


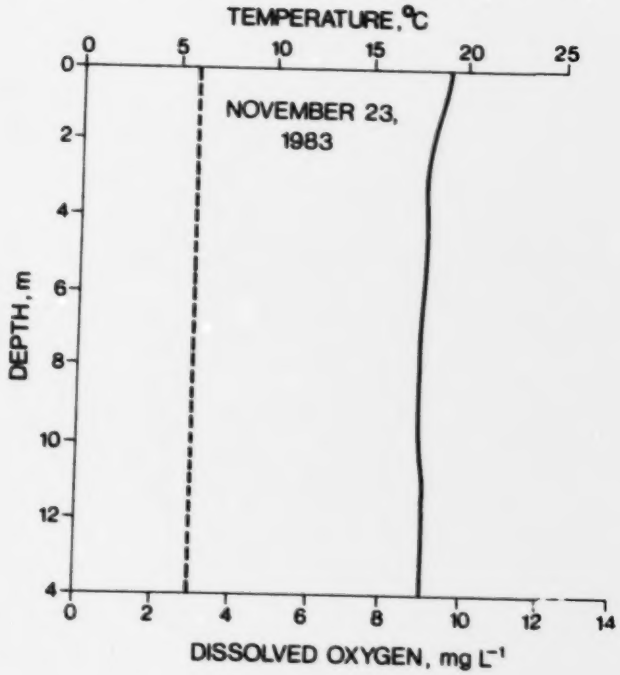


DISSOLVED OXYGEN ——————
TEMPERATURE - - - - - - -

LAKE THOMAS







DISSOLVED OXYGEN ———
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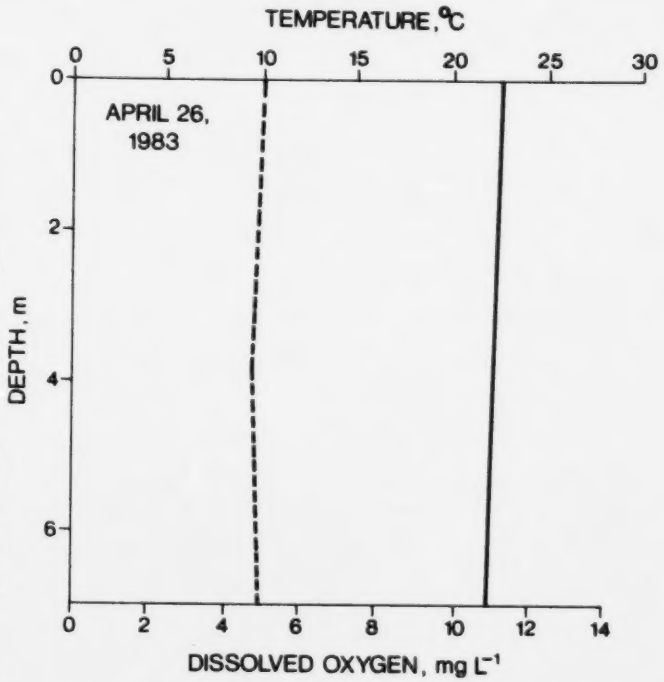
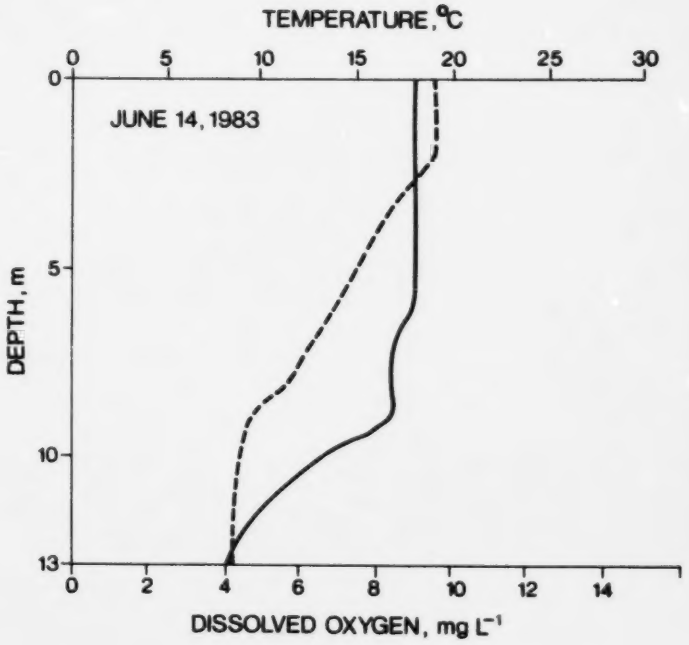
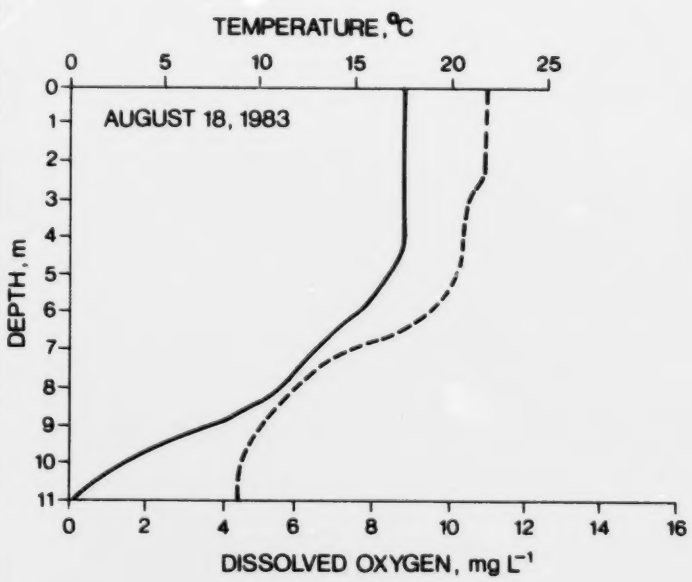
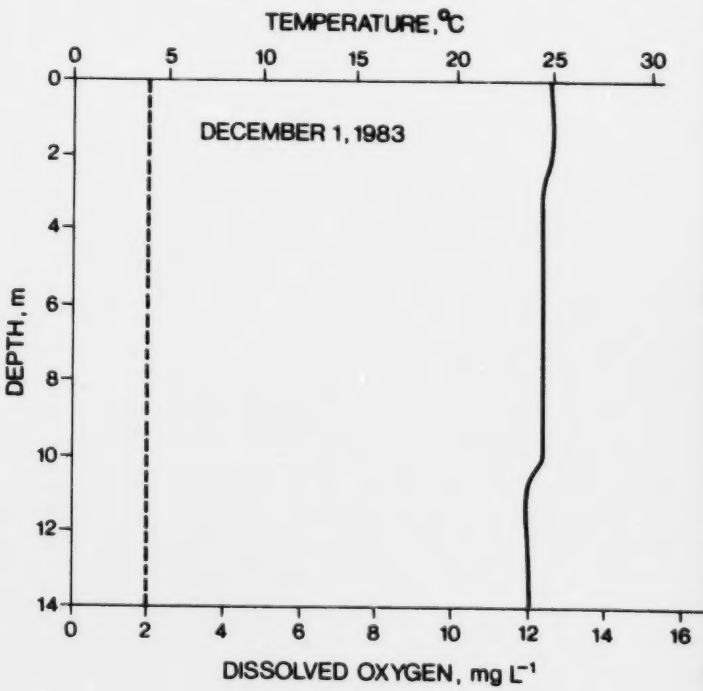
POWDER MILL LAKE



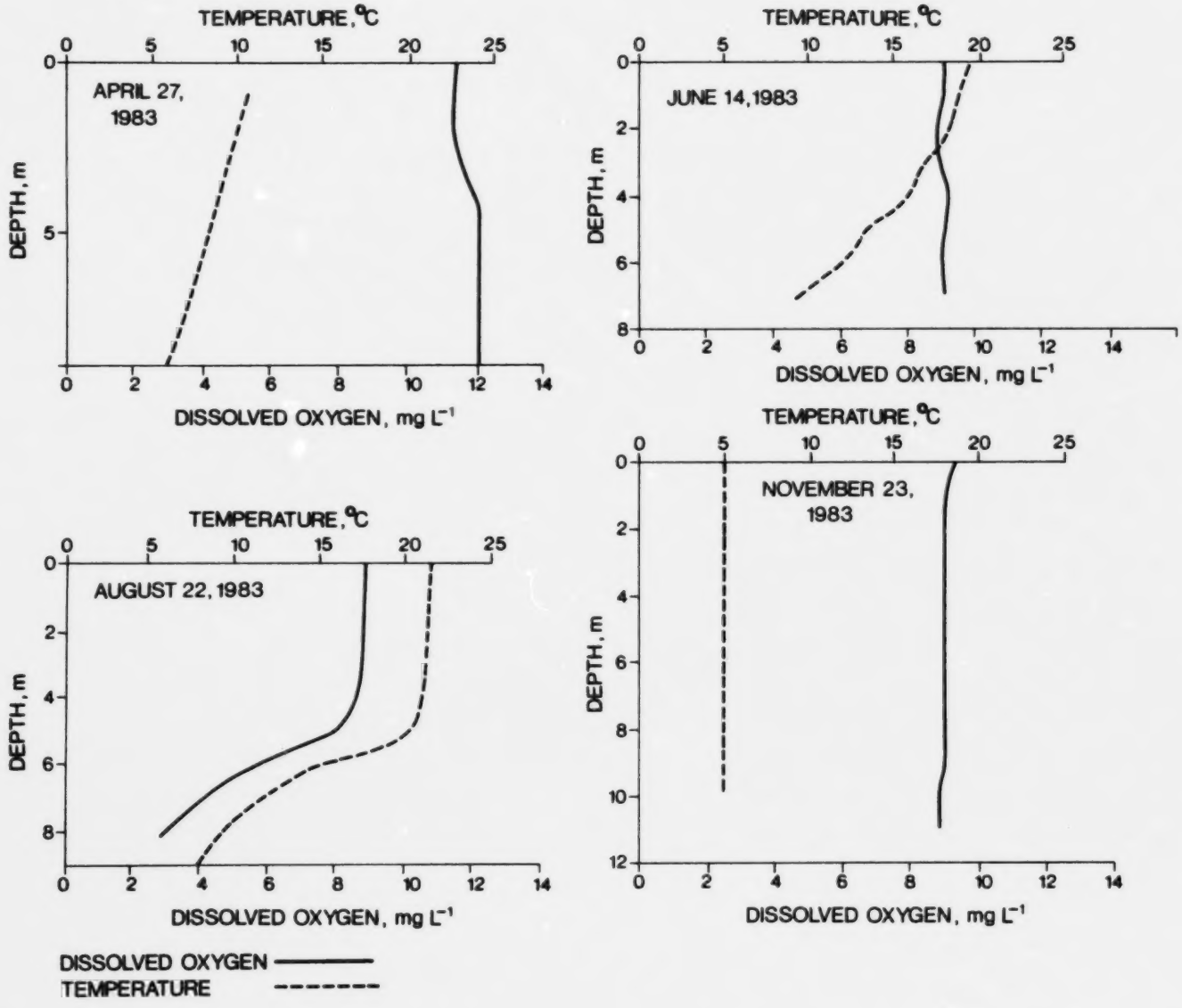




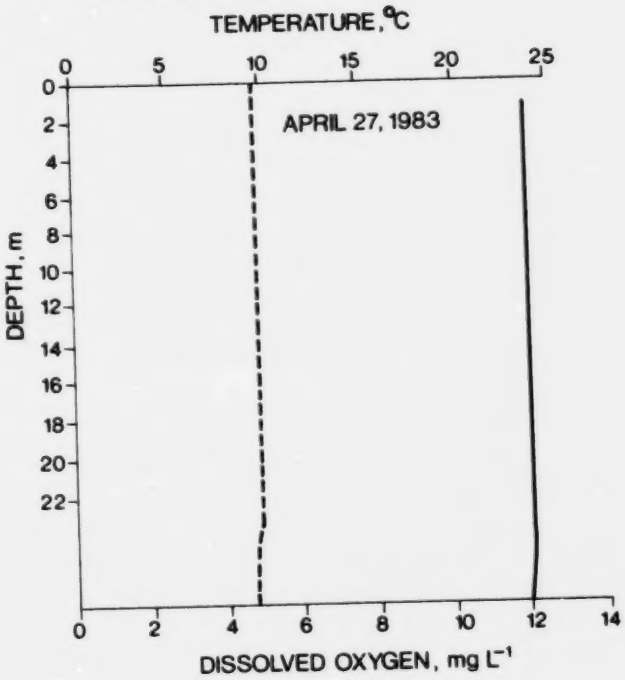


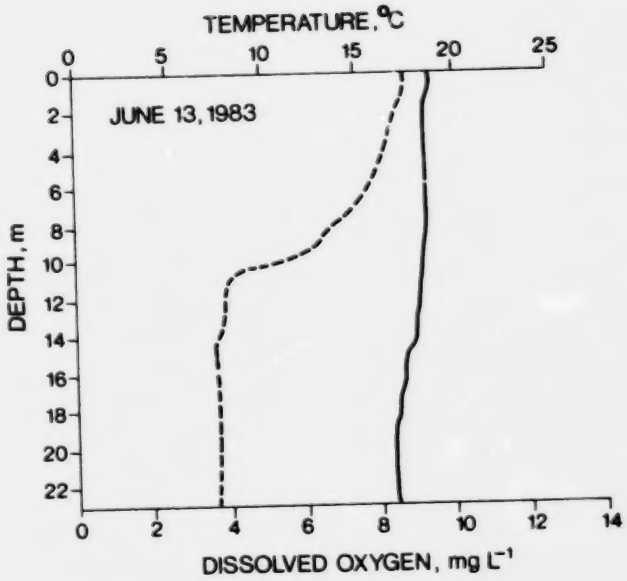
DISSOLVED OXYGEN ———
TEMPERATURE - - - - - -

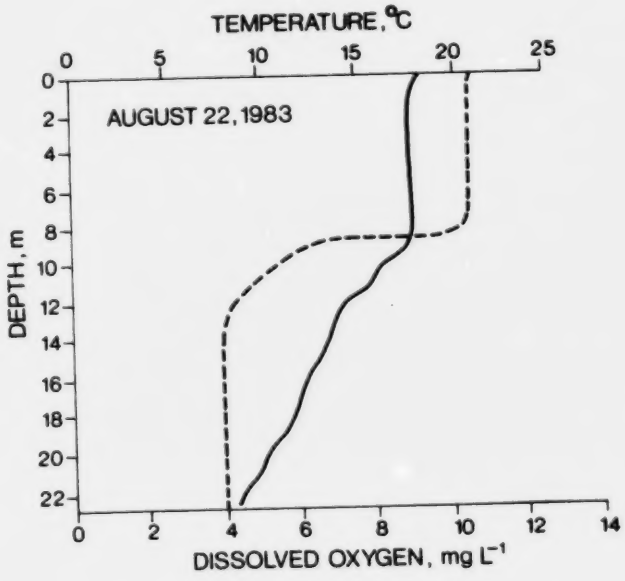
THREE MILE LAKE

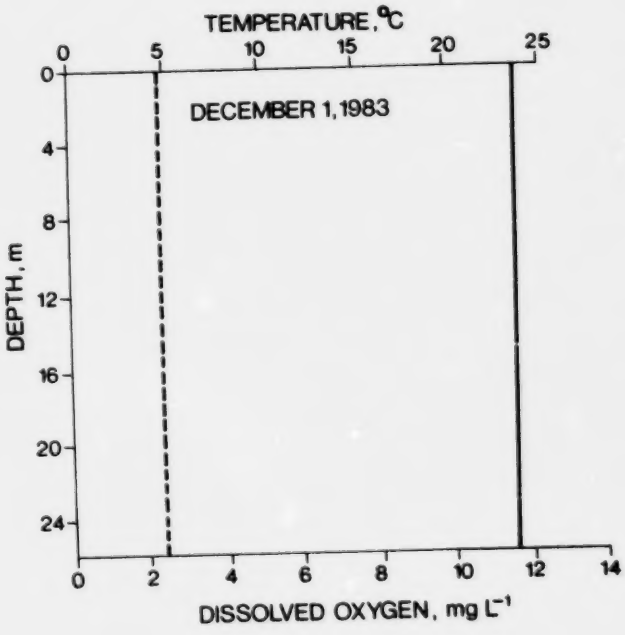


THIRD LAKE



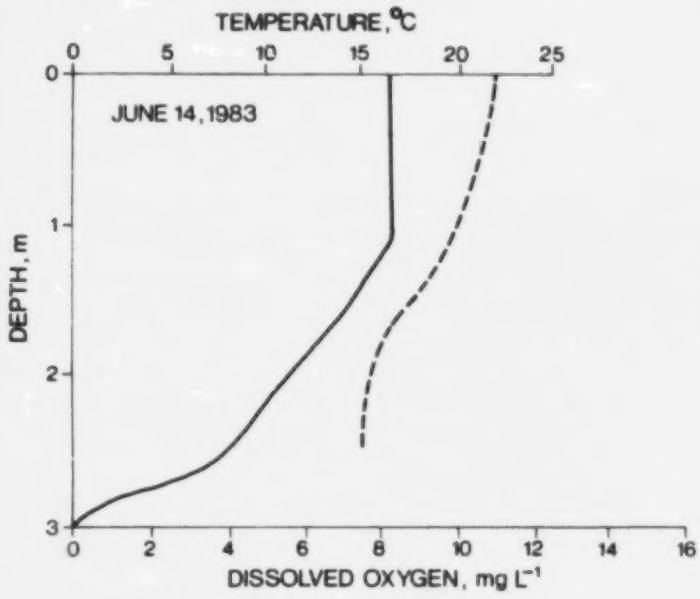


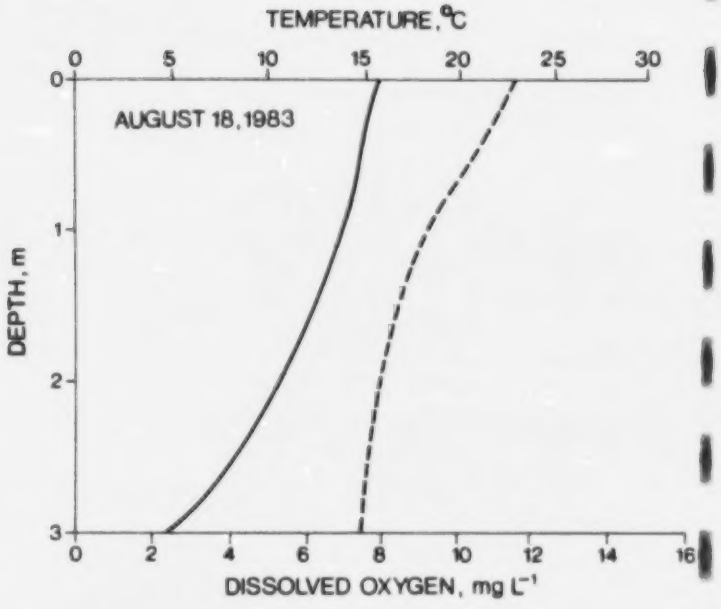


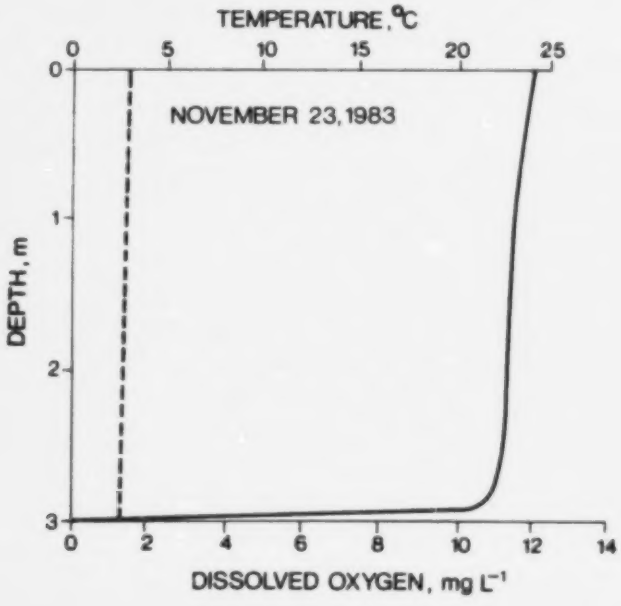


DISSOLVED OXYGEN ——————
TEMPERATURE - - - - - - -

MUDDY POND







DISSOLVED OXYGEN ——————
TEMPERATURE - - - - - - -

levels were homogeneous and at saturation levels in all lakes in April and in November except for Fletcher Lake where there was a decrease of 4 $mg.L^{-1}$ between top and bottom in the fall. Whereas the major factor influencing thermal stratification is the solar energy received at the surface of the lake, the major factor influencing dissolved oxygen stratification is the bio-chemical oxygen demand (BOD) of the sediments. The major result of BOD is that oxygen levels nearer the surface of sediments are lowered as bacterial decomposition of organic debris takes it up. As the lake warms up and creates a thermocline, the waters near the bottom (the hypolimnion) are then isolated from the atmosphere with which they usually exchange oxygen. The result of this series of events is that the oxygen levels in deeper water are lowered over the summer and only return to saturation levels after stratification breaks down.

This pattern is seen in almost all the large lakes that were studied (Fig. 1 to Fig. 6). In June, DO levels were somewhat lower near the sediment-water interface than at the surface. In August, the development of the D.O. curve is more pronounced in all lakes except Fletcher. The same explanations given for the temperature profile of Fletcher Lake probably also apply for the D.O. curve.

Major Ions

Table 2 gives results of the major ion analyses for the study lakes. The values show a system heavily influenced by sodium

Table 2. Range of Major Ion Values at Study Sites. The Order of Sites in the Table Show their Relative Order in the Watershed

	pH	Colour rel. units	Alk $mg.L^{-1}$	SO_4 $mg.L^{-1}$	Chloride $mg.L^{-1}$	Sodium $mg.L^{-1}$
System A						
Third Lake						
Apr 27 (3 depths)	6.5-6.6	5	3.3-3.5	5.8-5.9	16	9.2- 9.4
Jun 13 (3 depths)	6.1	L5	3.5-3.7	6.1	14.0-14.5	8.7- 8.8
Aug 18 (5 depths)	6.1-6.4	L5-5	3.5-4.1	5.7-6.1	14.8-15.0	9.0- 9.2
Dec 1 (3 depths)	6.4-6.5	L5	2.9-3.9	5.3-5.5	14.5-14.9	8.6- 8.7
Three Mile Lake						
Apr 27 (3 depths)	6.4-6.5	5	3.8-4.8	6.2-6.6	18-20	10.2-11.4
Jun 14 (3 depths)	6.3-6.4	5	4.3-5.1	6.7-7.2	14.7-18	9.0-10.1
Aug 22 (5 depths)	6.2-6.4	L5-5	5.4-7.9	6.3-6.9	17-23	9.7-12.1
Nov 23 (3 depths)	6.5-6.6	5	5.4-5.2	6.0-6.1	14.0-14.9	9.2- 9.3
Stream from Three Mile to Powder Mill Lakes						
May 5	6.6	5	4.4	6.2	20	11.1
June 15	6.5	5	5.2	6.1	19	10.5
Aug 22	6.3	5	6.4	6.3	21	11.7
Nov 23	6.4	5	5.8	6.2	19	10.2
Feb 16	6.3	15	3.8	6.0	21	11.0

Table 2. Cont'd.

	pH	Colour	Alk	SO_4	Chloride	Sodium
System A						
Powder Mill Lake						
Apr 26 (3 depths)	6.7-6.9	5	7.7- 8.1	8.5-8.7	30	17.2-17.5
Jun 14 (3 depths)	6.5-6.7	5	7.9- 8.6	8.1-8.5	28-31	15.0-16.4
Aug 18 (4 depths)	6.3-6.6	L5-5	8.3-10.1	8.1-8.7	26-29	15.7-17.0
Dec 1 (3 depths)	6.7-6.8	L5-5	9.0- 9.2	7.4-7.5	27-29	15.0-15.6
Stream from Powder Mill Lake to Lake William						
June 13	6.2	L5	8.0	8.6	28	15.4
Aug 19	6.5	5	8.9	8.1	27	15.4
Nov 23	6.9	L5	9.8	7.4	29	15.9
Feb 16	6.4	10	5.4	6.9	24	13.0
Stream from Lake William to Lake Thomas						
May 5	6.6	10	4.0	8.3	25	15.6
June 14	6.3	5	4.0	8.1	26	14.4
Aug 22	6.3	5	5.0	8.2	26	14.2
Nov 23	6.6	5	5.2	7.4	25	13.8
Feb 16	6.4	20	3.8	5.3	23	13.1

Table 2. Cont'd.

	pH	Colour	Alk	SO_4	Chloride	Sodium
System A						
Lake Thomas						
May 5 (3 depths)	6.5-6.6	5-10	4.4- 4.5	8.3-8.5	26	15.0-15.2
Jun 14 (3 depths)	6.3-6.5	5	4.7- 4.8	8.1	25-27	14.3-14.5
Aug 17 (4 depths)	6.1-6.5	5	5.5- 8.2	8.3-8.7	26	14.4-15.5
Nov 23 (3 depths)	6.5-7.3	25-5	1.1- 3.1	7.2-7.6	25	13.8-13.9
Stream from Lake Thomas to Lake Fletcher						
May 5	6.4	5	2.9	8.6	22	13.4
June 14	6.4	5	3.4	8.1	22	12.5
Aug 22	6.3	L5	4.3	8.4	23	13.3
Nov 23	6.5	5	3.5	7.9	20	11.3
Feb 16	6.2	25	2.7	8.0	25	14.2
Lake Fletcher						
Apr 26 (3 depths)	6.4	5	1.9-2.8	8.3-8.4	23-24	13.7-13.8
Jun 23 (3 depths)	6.1-6.4	5	3.2-3.7	8.1-8.6	21-22	12.2-12.3
Aug 23 (3 depths)	6.3-6.4	L5-5	4.2-4.4	8.2	22-24	12.9-13.1
Nov 22 (3 depths)	6.3-6.5	L5-5	0.3-1.8	7.6	18-19	10.4-10.5

Table 2. Cont'd.

	pH	Colour	Alk	SO_4	Chloride	Sodium
System B						
Perry Lake						
May 5 (1 depth)	6.2	5	2.1	5.9	11.8	7.9
Jun 15 (1 depth)	6.2	5	2.4	6.1	10.4	6.8
Aug 16 (1 depth)	6.1	L5	2.8	6.3	10.8	6.7
Dec 1 (1 depth)	6.3	10	2.4	5.3	9.6	5.9
Muddy Pond						
May 5 (1 depth)	6.4	35	5.4	6.7	29	17.2
June 14 (1 depth)	6.2	35	5.1	5.0	28	14.7
Aug 18 (1 depth)	6.1	55	5.7	6.5	33	18.7
Nov 23 (1 depth)	6.1	55	5.7	6.5	33	18.7
Stream from Muddy Pond to Lake Thomas						
May 5	6.6	30	8.2	7.2	32	18.8
June 13	6.3	25	10.3	5.5	28	16.1
Aug 17	6.5	35	10.5	6.2	33	18.2
Nov 23	6.6	50	7.0	6.2	19	10.7
Feb 16	6.3	20	4.6	5.8	31	17.0

chloride. Salts of marine origin often dominate the major ion chemistry of lakes near sea coasts in the region and this is an effect which must be taken into account when studying certain major ions in freshwaters. As chloride, sodium, calcium, magnesium, potassium and sulfate are found in standard ratios in seawater, it is assumed that these ratios are carried over in the sea-spray. As chloride can usually be considered to be completely of marine origin, a correction using the ratios between chloride and the other ions can be applied. Watt et al. (1979) and Thompson (1982) fully explained the uses of corrections. Though there is a marine influence to the study lake water chemistry, there also seems to be a major influence of road salt. The only lake studied with no roads near it is Perry Lake. Chloride values here range between 9.6 and 11.8 $mg.L^{-1}$, while sodium ranged from 5.9 to 7.9 $mg.L^{-1}$. Values from Third Lake, at the head of System A, also ranged from 14 to 16 and 8.6 to 9.4 $mg.L^{-1}$, respectively, values which were within the range of undisturbed lakes in the Halifax area reported by Watt et al. (1979). As these two parameters are followed down the two watersheds, however, chloride and sodium values triple for System B and nearly double in System A. As there is no large difference in the lakes' distances from the coast and as the lower parts of the basins are crisscrossed with roads, it must be assumed that road salt, which is heavily used in the area contributes to lake water NaCl levels. Chloride then cannot be used for estimating sea-salt contributions of calcium, magnesium and sulfate which are used in estimating acidification effects. In the

case of this work, we will assume that the road-salt contribution to Cl levels has remained constant over the years.

All lakes show relatively high pH values and alkalinities. However, when compared to data collected in 1976 (Johnson 1978) for six sites, an interesting pattern emerges. Values of pH at all sites except at Fletcher Lake have decreased (Table 3) a phenomenon also shown by Watt et al. (1979) for other lakes in the region. Alkalinity values have also increased at all sites except for at the bottom of Lake Thomas. The decreases in pH are similar to those reported by Watt et al. (1979), as are the increases in alkalinity. Watt et al. (1979) also show no differences in sea-salt corrected sulfate, though these results are impossible to confirm due to the inability of correcting for sea-salt influence.

The major ion data point out the great importance that road salting operations have on major ion quality. The changes measured in NaCl are the main indication of this problem, but other parameters such as $SO_4^{=}$, Ca^{++} and Mg^{+} might also be affected, depending on the salt's composition. Despite the influence of road maintenance on the lakes' water quality, none of the major ions measured exceeded any water quality objectives for drinking water or aquatic life (McNeeley et al. 1979) nor did they show abnormal seasonal patterns.

Metals

The standards used to compare Shubenacadie Lake water metal content to levels acceptable for drinking water supplies and aquatic

Table 3. Comparison of major ion parameters between 1976 and present study

	pH	Alk $mg.L^{-1}$	SO_4 $mg.L^{-1}$	Cl $mg.L^{-1}$	Ca $mg.L^{-1}$	Na $mg.L^{-1}$	NO2-NO3 $mg.L^{-1}$
Lake William - Lake Thomas outflow							
1976	6.8	3.5	7.5(5.0)	18	4.0	10	L0.1
1983	6.3	5.0(8.0)	8.2(4.8	26	5.0	14.2	L0.01
Lake Thomas - surface							
1976	6.7	3.8	9.5	18.5	4.1	11	L0.1
1983	6.5	5.5	8.8	26	5.0	14.4	L0.01
Lake Thomas - bottom							
1976	6.3	11	7.2	19	5.4	11	L0.1
1983	6.2	8.2	8.2	26	5.4	15.5	0.18
Lake Thomas - Lake Fletcher							
1976	6.6	3.0	9.5	17	3.8	9.8	L0.1
1983	6.3	4.3	8.0	23	4.5	13.3	0.01
Lake Fletcher - surface							
1976	6.3	1.5	8.0	17	3.4	9.9	L0.1
1983	6.4	4.2	8.3	22	4.3	12.9	L0.01
Lake Fletcher - bottom							
1976	6.1	1.5	8.0	17	3.4	9.7	L0.1
1983	6.4	4.4	8.2	22	4.4	12.9	L0.01

life are shown in Table 4. It will be noted that the standards are usually higher for aquatic life than for human consumption due to the fact that aquatic life is continuously in contact with contaminants and so are more likely to accumulate them than humans.

The metals which were analyzed but went undetected in the waters in this study were: mercury, chromium and cobalt. As the detection limits are well below the standards set, it can be assumed that these metals in water present no problems for human or aquatic life use.

Parameters which were measurable, but at levels below standards were: lead, zinc, nickel, aluminum and arsenic (Appendix III). Of these only arsenic was found at sufficiently high levels to justify further data analysis. The levels measured for arsenic are all within acceptable limits for drinking water and aquatic life. Demayo *et al.* (1979) reports that, in data from Canadian rivers, arsenic ranged from 0.001 to 0.05 $mg.L^{-1}$, with 90% of all values being below 0.008 $mg.L^{-1}$. In lakes, their reported values ranged from 0.005 to 0.02 $mg.L^{-1}$. In this study, values ranged from less than 0.002 to 0.047 in the Muddy Pond outflow, though in System A which went from Third Lake to Fletcher Lake, the highest value was 0.0058 $mg.L^{-1}$ in Lake Thomas in August. There was a minor trend of increasing levels of arsenic, going down System to Lake Thomas. Another trend noted was an increase of arsenic levels with temperature increases, though no correlation with dissolved oxygen levels was found.

Table 4. Metals Analyzed for the Study. Water Quality Standards for Drinking Water Supplies and Aquatic Life are also Included from McNeely et al. (1980) and Demayo et al. (1979)

Metal	Chemical Symbol	NAQUADAT Code	Detection Limit (in $mg.L^{-1}$)	Standards (in $mg.L^{-1}$)	
				Drinking Water	Aquatic Life
Iron	Fe	26304P	0.05	0.3[1]	0.3
Arsenic	As	33007L	0.001	0.05	0.05
Mercury	Hg	80315P	0.02 $ug.L^{-1}$	0.001	0.0002
Copper	Cu	29305P	0.002	0.5	0.002
Lead	Pb	82302P	0.002	0.25	0.005
Zinc	Zn	30304P	0.01	5.0	0.05
Cadmium	Cd	48302P	0.001	0.01	0.002
Cobalt	Co	27003P	0.001	1.0	-
Nickel	Ni	28007L	0.001	0.25	0.025
Manganese	Mn	25304P	0.01	0.2	0.02
Aluminum	Al	13305P	0.002	5.0	0.1
Chromium	Cr	24004L	0.0005	0.1	0.04

[1]For taste only, no danger to human life.

The behaviour of arsenic in System B shows a different pattern. Perry Lake over the study period had arsenic values below or near the detection limit, as did the other headwater lake in the study, Third Lake. Muddy Pond and its outflow, however, show a different picture. Values measured ranged from 0.0061 to 0.047 $mg.L^{-1}$ and the lower value was higher than the highest value in System A. The outflow values were also higher than the lake results, probably due to particles in the water which were not filtered out. This is borne out by samples collected in November where unfiltered results were 33% higher than filtered. Nevertheless, outflow values were very near the acceptable limit for either human or aquatic life use. Muddy Pond outlet is near the public swimming beach on Lake Thomas and this shows some cause for concern. Not enough data were available to draw major conclusions, but no relationship seemed to occur between arsenic in lake or outflow waters with either dissolved oxygen, temperature or the water discharge rate from the brook.

Of the remaining parameters measured, aluminum values were generally very low, and present little concern at the relatively high pH values found in the basin (Baker & Schofield, 1982). It is noted, however, that no aluminum values were recorded in the April-May sampling due to sampler contamination, and that values in the June sampling were higher than for the others. Lead values were generally below the detection limit, and the measurable values tended to be in August when water temperature was warmest, though no correlation with low dissolved oxygen was found. Nickel values were not recorded in

April-May. However, using the remaining values, no correlations could be drawn between Ni and dissolved oxygen or water temperature.

The only parameters which exceeded guidelines at any time during the study were iron and manganese, though the levels set are mostly for aesthetic and taste reasons. The high values of manganese and iron that are found in Powder Mill and Muddy Pond occur only in the summertime under conditions of low oxygen. This phenomenon is well understood and the values from this study are not unusual for waters low in dissolved oxygen (Hutchinson, 1957).

High values for arsenic, iron and manganese in Muddy Pond are not surprising, as the area contained a gold processing plant (Tripp, this report), and high levels of arsenic have been measured in the tailings and sediments. The high level of macrophyte production in the Pond also ensures that large amounts of decomposing plants lower the dissolved oxygen levels during the summer. Under lowered D.O. levels, exchanges of certain metals between sediments and overlying water are more likely to happen.

ACKNOWLEDGEMENTS

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ESTIMATION OF STATES OF EUTROPHY OF SEVERAL SHUBENACADIE HEADWATER LAKES BY COMPARISON OF PHOSPHORUS LOADING WITH SECCHI TRANSPARENCY AN OXYGEN DEPLETION RATES

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INTRODUCTION

Lakes may be classified in accordance with their productivity resulting from nutrient contents. While Liebig's law of the minimum defines the conditions whereby any substance may retard growth rates, contemporary limnological studies very frequently associate phosphorus with being the key nutrient (e.g. Vollenweider and Kerekes, 1980). Although many lakes not affected by development will age through natural ecological succession from an oligotrophic (poorly fed) state through to a mesotrophic (moderately fed) condition and finally to a eutrophic (well fed) stage, anthropogenic sources of phosphorus will accelerate the aging succession. Such sources include lawn fertilizers, detergents and sewage (Vallentyne, 1974).

The Shubenacadie headwater lakes have been under frequent investigation for about ten years. The land from Halifax to the upper Shubenacadie River (Fig. 1) has been considered the area of the province likely to receive the most intense development before the turn of the century. Consequently, in the mid 1970's a joint Federal-Provincial agreement was negotiated to study the watershed of the Shubenacadie River. One part of the study was the examination of nutrient status of nine Shubenacadie headwater lakes (Hart, Scott and Ogden, 1978). The investigators used a now largely outdated classification scheme and concluded that those lakes had low nutrient concentrations and were considered oligotrophic.

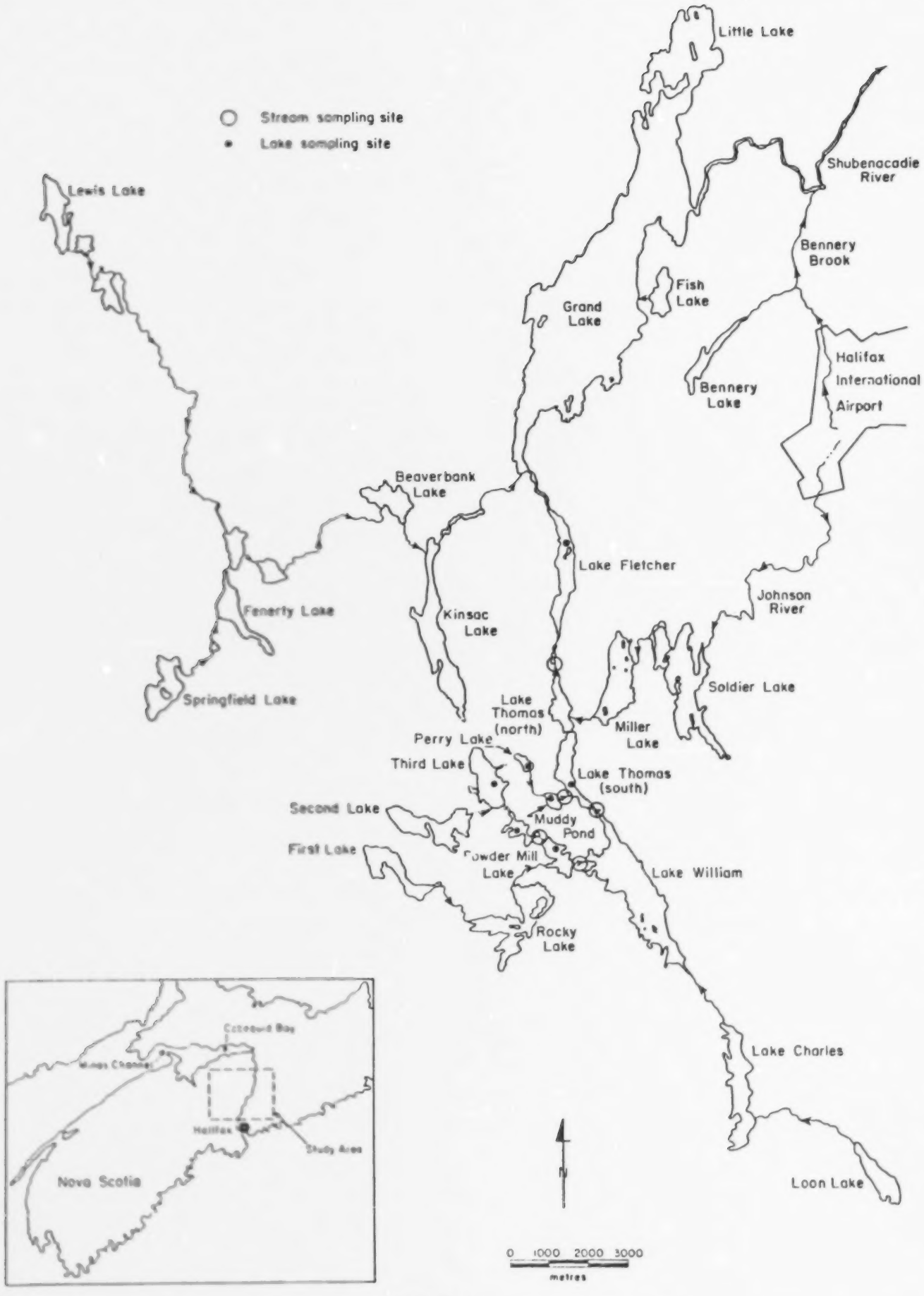
Stream sampling site
Lake sampling site
Little Lake
Shubenacadie River
Lewis Lake
Bennery Brook
Fish Lake
Grand Lake
Halifax International Airport
Bennery Lake
Beaverbank Lake
Lake Fletcher
Johnson River
Fenerty Lake
Kinsac Lake
Soldier Lake
Springfield Lake
Lake Thomas (north)
Miller Lake
Perry Lake
Third Lake
Lake Thomas (south)
Second Lake
Muddy Pond
First Lake
Powder Mill Lake
Lake William
Rocky Lake
Lake Charles
Loon Lake
Nova Scotia
Halifax
Study Area
N
0 1000 2000 3000
metres

FIGURE 1

Ogden (1972) examined several of the lakes in 1971 and his data form a valuable part of the historical record on the lakes.

In 1983 several headwater lakes were identified for the sensitivity to watershed disturbances. While the particular concerns focussed on arsenic and mercury in lake sediments, it was recognized that biogeochemical cycles of these metals are intricately linked to oxidation-reduction phenomena which, in turn, are very much a function of productivity in lakes. Thus, the present study was conducted in order to assess the current trophic status of seven headwater lakes of the Shubenacadie Basin system. The method of assessment incorporated phosphorus concepts that were developed by the Organization for Economic Cooperation and Development (OECD) research (Vollenweider and Kerekes, 1980). Flushing rates and whole lake phosphorus concentrations were used to estimate phosphorus loadings from watersheds. In addition, measured values of phosphorus concentrations and flow rates in streams were assessed in order to compare with results obtained from the lake concentrations. As no chlorophyll data were collected, the lakes were also assigned states of eutrophy based on Secchi disc transparencies and dissolved oxygen contents.

Once study lakes had been tentatively classified, attempts were made to determine the capacity of the lakes to withstand additional phosphorus loading before reaching the next level of trophic magnitude.

METHODS

Water was sampled in lakes Powder Mill, Third, Three Mile, Thomas, Fletcher, Perry and Muddy Pond and in the connecting streams four times during the study period between April and December of 1983. Samples were collected at the deepest point of each lake, except for Perry Lake, where only shore sampling was possible. A two-litre Van Dorn sampler was used to collect samples from 1 m below surface, middle of the water column and 1.5 m above the bottom. Additional water samples were taken during the months when the lakes were thermally stratified.

Dissolved oxygen and temperature was measured in the field by a YSI oxygen meter (model no. 57). A 20 cm Secchi disc was used to measure transparency. Phosphorus and nitrogen were analyzed in water samples according to the Water Quality Branch, Inland Waters Directorate, 1979. Morphometric data on most study lakes were acquired from the Shubenacadie Headwaters Environmental Survey (IWD, 1974). Morphometric data for Three Mile Lake were obtained from the Metropolitan Area Planning Committee report (MAPC, 71-72). The morphometry of Muddy Pond was calculated from bathymetry soundings conducted by Nova Scotia Department of the Environment (NSDOE) in September of 1982. Flushing rates for the study lakes were obtained from MAPC (71-72) and Johnson (1978). However, the values were used with standard precautions because of the short-term data base. The flushing rate for Muddy Pond was calculated using a runoff coefficient

of 0.64 found in the Hydrological Atlas of Canada, compiled by the Canadian National Committee for the International Hydrological decade (CNC/IHD, 1978). Watershed areas for Muddy Pond and Perry Lake were calculated from a 1:10,000 orthophoto, with the assumption that the roads within the drainage area contain culverts that do not impede natural drainage. Stream flow measurements were obtained from Water Resources Branch, Inland Waters Directorate (1984).

Trophic classifications were derived from OECD probability curves for phosphorus and Secchi readings (Vollenweider and Kerekes, 1980) and hypolimnion oxygen concentrations, using the Theienemann trophic scale (Chapra and Dobson, 1981).

Mean phosphorus concentrations in the lakes were calculated by adjusting for water volumes at each depth. In addition to whole-lake mean values for phosphorus, theoretical input from watershed soils was estimated by rearranging an OECD relationship (Fig. 6.11 of Vollenweider and Kerekes, 1980).

$$[\overline{P}]_i = \left[\frac{[\overline{P}]_\lambda}{1.55}\right]^{1.22} \cdot (1 + \sqrt{T(w)}) \qquad (1)$$

Symbols for watershed parameters used throughout the report follow, where possible, Vollenweider and Dillon (1974) such that:

- Ad is the area of the watershed to the outlet of a lake, exclusive of that lake, measured in m^2.
- Ad_i is the area of the immediate watershed surrounding a lake in m^2.
- Ad_c is the total or cumulative drainage area of a lake, measured in m^2. This includes watersheds and lakes upstream of the lake of immediate interest, but excludes the surface area of the study lake.
- Q_s is the areal water loading to a lake, measured in $m^3.y^{-1}$.
- T(w) is the residence time of water in years.
- $[\overline{P}]_\lambda$ is the mean annual phosphorus concentration in the lake, measured in $mg.m^{-3}$.
- P_λ is the total amount of phosphorus in the lake, measured in mg.
- $[\overline{P}]_i$ is the mean phosphorus concentration of inlet waters ($mg.m^{-3}$) according to equation 1.
- P_i is the total input of phosphorus (mg) from the watershed according to concentration ($[\overline{P}]_i$) and volumes of inlet streams.
- Es_i is the phosphorus export coefficient from soils in the immediate watershed area, measured in $mg.m^{-2}$ of watershed.
- Es_c is the phosphorus export coefficient from soils in the cumulative watershed area ($mg.m^{-2}$).

RESULTS

Phosphorus and Nitrogen Ratios and OECD Classification of Lake Trophic Status

Mean annual total phosphorus $[\overline{P}]$ and total nitrogen $[\overline{N}]$ concentrations are presented in Table 1. Third Lake was found to contain the lowest $[\overline{P}]$ with 3.5 $mg.m^{-3}$. Phosphorus concentrations ranged from 3.5 to 18 $mg.m^{-3}$, and the mean value was 7.6 $mg.m^{-3}$. OECD lakes ranged from 3.0 to 750 $mg.m^{-3}$ (mean value of 47.1), while other Nova Scotia lakes are reported to range from 2 to 20 $mg.m^{-3}$ with a mean value of about 8 $mg.m^{-3}$ (Vollenweider and Kerekes, 1980; Kerekes, 1983).

Total nitrogen concentrations (Table 1) varied from 100 to 190 $mg.m^{-3}$ (mean value 140 $mg.m^{-3}$) and were smaller than those reported for OECD lakes (263 to 6095, $\overline{x}$ = 1244 $mg.m^{-3}$; Vollenweider and Kerekes, 1980).

Ratios of [total N]:[total P] were calculated to investigate if phosphorus was the probable limiting nutrient. Fricker (1981) reported that total phosphorus is the limiting nutrient when the ratio is greater than 17. Table 1 indicates that the ratio was slightly less than 17 in Muddy Pond and lakes Three Mile and Fletcher. This ratio indicates that nitrogen could stimulate production in these lakes. However, more data need to be collected to verify this speculation since concentrations of N and P are low relative to the working range of the OECD lakes.

Table 1. Mean Annual Concentration of Phosphorus and Nitrogen Including Corresponding OECD Trophic Classifications

Lake Name	Mean Annual Total Phosphorus Concentration	Mean Annual Total Nitrogen Concentration	TN/ /TP	OECD Classification
Third	3.5	140.0	40	Ultra-Oligotrophic
Three Mile	7.0	120.0	17	Oligotrophic
Powder Mill	6.5	120.0	18	Oligotrophic
Perry	4.5	150.0	33	Oligotrophic
Muddy Pond	18.0	190.0	11	Mesotrophic
Thomas	8.0	160.0	20	Oligotrophic
Fletcher	6.0	100.0	16	Oligotrophic

Phosphorus concentrations were compared with OECD probability curves (Vollenweider and Kerekes, 1980) in order to classify the theoretical status of eutrophy of the study lakes. Table 1 indicates that while most of the lakes are oligotrophic, Third Lake would appear to be ultra-oligotrophic, while Muddy Pond is mesotrophic by this classification.

Whole Lake Phosphorus Concentrations and Estimates of Phosphorus Loadings from Watersheds

In order to determine the input of total phosphorus from the various watersheds, a phosphorus budget was developed based on the mean phosphorus concentrations of inlet waters, calculated according to equation 1. It is necessary to consider phosphorus concentrations of inlet waters in addition to the whole-lake phosphorus concentrations, as use of inlet values allows for accommodation of phosphorus that is lost through sedimentation, macrophyte assimilation, and flow through the lakes.

Table 2 shows the calculated export coefficients of phosphorus from both the immediate and cumulative watersheds of the study lakes. The export coefficients Es_i and Es_c are calculated by dividing the total input of phosphorus from the watershed by the areas of the immediate and cumulative watersheds, respectively.

The phosphorus export coefficients (Es_i), calculated for the immediate watershed areas of the lakes ranged from 40.5 $mg.m^{-2}$ for Three Mile Lake watershed to 165 $mg.m^{-2}$ for Lake Thomas watershed. The arithmetic mean phosphorus export coefficient was found to be 94 $mg.m^{-2}$. Lakes Thomas, Powder Mill, and Muddy Pond show export coefficients greater than the calculated mean.

Estimates for the phosphorus export coefficient (Es_c), based on the cumulative watershed areas of study lakes, ranged from 2.8 $mg.m^{-2}$ for Three Mile Lake to 23.7 $mg.m^{2}$ for Muddy Pond;

Table 2. Estimation of Phosphorus Export from Watersheds of Study Lakes
Abbreviations Explained in Section 2

Lake	Ad_i $m^2 x10^6$	Ad_c $m^2 x10^6$	q_s $m^3 x10^6$	Vol $m^3 x10^6$	T(w) year	$[\overline{P}]_\lambda$ $mg.m^{-3}$	P_λ $mgx10^6$	$[\overline{P}]_i$ $mg.m^{-3}$	P_i $mgx10^6$	Es_i $mg.m^{-2}$	Es_c $mg.m^{-2}$
Third	2.89	9.81	31.1	5.53	0.75	3.5	27.1	3.8	155.5	53.8	15.9
Three Mile	0.78	11.50	3.9	0.324	0.083	7.0	2.9	8.1	31.6	40.5	2.8
Powder Mill	2.51	26.22	48.4	1.84	0.038	6.5	14.4	6.9	334.0	133.1	12.7
Muddy Pond	0.24	1.26	1.3	0.032	0.025	18.0	0.67	23.0	29.9	124.6	23.7
Thomas	5.91	126.79	109.3	4.59	0.042	8.0	44.1	8.9	972.8	164.6	7.7
Fletcher	14.33	142.25	135.4	3.79	0.028	6.0	26.5	6.1	825.9	57.6	5.8

the mean being 9.8 $mg.m^{-2}$. Muddy Pond, Third and Powder Mill Lakes all showed phosphorus export coefficients greater than the mean. Three Mile Lake exports the least amount of total phosphorus, per unit area of both immediate and cumulative watersheds, in comparison with other study lakes.

Total phosphorus loading L(P), was also calculated per unit area of lake surface, in order to compare them with the minimum, maximum and mean values listed in the OECD report (Vollenweider and Kerekes, 1980). The L(P) ranged from 195 $mg.m^{-2}$ for Third Lake to 925 $mg.m^{-2}$ for Lake Thomas, with a geometrical mean of 506 $mg.m^{-2}$ for all study lakes. OECD minimum L(P) value was 17 $mg.m^{-2}$, with a geometrical mean of 1200 $mg.m^{-2}$. Kerekes (1983) found a L(P) value of 133 $mg.m^{-2}$ for Freshwater Lake in Cape Breton.

Estimates of Phosphorus Loadings to Lakes from Streams

Table 2 was used to examine whole lake phosphorus concentrations in order to estimate, by a "tailor-made" regression (equation 1), inlet concentrations and export coefficients. However, five streams interconnecting the study lakes were sampled during the study period, and daily discharge readings were taken at four of them. These measurements have provided an opportunity to compare estimates of inlet concentrations (Table 2) with actual measurements (Table 3).

Table 3. Estimation of Phosphorus Export Via Inlet Waters

Stream	Mean TP Concentration $mg.m^{-2}$	Average Discharge m^3/s	Transport of TP mg/s	Annual TP Loading $mg.m^{-2}$	TP Loading per Unit Immediate Watershed Area (Including Lake) Es_i; $mg.m^{-2}$	TP Loading per Unit Cumulative Watershed Area Es_c; $mg.m^{-2}$
Powder Mill to William	8.75	0.740	6.47	64.8 on William (204.1×10^6 mg)	P.M. W'shed to Wm. 69.66 of P.M. W'shed (2.93 km^2)	7.7 P.M. W'shed+(26.6 km^2)
William to Thomas	7.4	1.99	14.70	409.8 on Thomas (464.4×10^6 mg)	Wm. W'shed to Th. 15.00 of Wm. W'shed (30.95 km^2)	6.1 Wm. W'shed+(76 km^2)
Muddy Pond to Thomas	15.4	0.052	0.80	22.2 on Thomas (25.1×10^6 mg)	M.P. W'shed to Th. 86.55 of M.P. W'shed (.29 km^2)	19.2 M.P. W'shed+(2.3 km^2)
Thomas to Fletcher	5.2	3.76	21.1	631.1 on Fletcher (664.0×10^6 mg)	Th. W'shed to Fl. 94.32 of Th. W'shed (7.04 km^2)	5.2 Th. W'shed+(128 km^2)

Based on the mean total phosphorus concentrations and average discharges calculated for the streams, the annual total phosphorus loading to three downstream lakes from the immediate and cumulative upstream watersheds were calculated. The lowest annual total phosphorus loading, calculated per unit immediate watershed area (Es_i), was for Lake William watershed to Lake Thomas, (15 $mg.m^{-2}$). The highest was 94 $mg.m^{-2}$ calculated for Lake Thomas watershed to Lake Fletcher. The arithmetic mean phosphorus contributions from the immediate watersheds of the four upstream lakes was 66 $mg.m^{-2}$.

The total phosphorus loading, calculated per unit cumulative watershed (Es_c) ranged from 5.2 $mg.m^{-2}$, contributed by the total drainage area of Lake Thomas, to 19.2 $mg.m^{-2}$ contributed by the total drainage area of Muddy Pond. The arithmetic mean contributions from cumulative watersheds was 9.6 $mg.m^{-2}$.

The corresponding export coefficients calculated per cumulative watershed area (Es_c) from Table 2 and Table 3 were compared. The export coefficient of phosphorus (Es_c) calculated for the Lake Thomas watershed using whole lake concentrations was 5.8 $mg.m^{-2}$ and 5.2 $mg.m^{-2}$ using stream concentrations. For the Muddy Pond watershed, the Es_c calculated from whole lake concentrations was 23.7 $mg.m^{-2}$ and 19.2 $mg.m^{-2}$ based on stream concentrations. Lake William watershed had Es_c of 7.7 $mg.m^{-2}$ calculated from whole lake concentrations and 6.1 $mg.m^{-2}$ based on stream concentrations. In the case of Powder Mill Lake watershed the Es_c calculated from whole lake concentrations was 12.7 $mg.m^{-2}$ and 7.7 $mg.m^{-2}$ based on stream concentratons.

Different figures calculated for Es_c using whole lake concentrations and stream concentrations arised from the fact that streams are more instantaneous indicators of watershed conditions. Consequently, fluctuations may occur; however, lakes might be considered as integrators of fluctuations over time because their larger volumes tend to dampen fluctuations in inlet waters.

Relationships between Streamflow and Phosphorus Concentrations

Calculations of phosphorus loadings to the lakes were based on instantaneous phosphorus concentrations and instantaneous flow rates in streams interconnecting study lakes. Instantaneous flows are strongly influenced by rapid variations in weather, so there were some concerns about extrapolation of point-source discharge data into estimates of monthly (or longer) phosphorus loading. Figures 2-5 compare phosphorus concentrations with daily and mean monthly flows of four study streams that were sampled three or four times throughout the study period. As this charge was compared with phosphorus concentrations in these figures, there was also an opportunity to determine if phosphorus concentrations were influenced by rates of flow.

Ratios calculated for daily discharges over monthly discharges ranged from 0.78 to 1.7 with the arithmetic mean being 1.25. The ratios for the month of August were consistently high while the ratios for February were consistently low. Using the mean value,

one could conceivable deduce that daily discharges were representative of monthly discharges.

Based on daily discharge curves, an apparent relationship existed between flow rates and phosphorus concentrations in the mainstream of the Shubenacadie system (i.e. Lakes William to Thomas, and Thomas to Fletcher, Figures 3 and 5 respectively). Regressions on daily discharge rates produced r^2 values of 0.85 and 0.97. A relationship is not evident in the secondary streams (i.e. Powder Mill to William and Muddy Creek; Figures 2 and 4 respectively).

This phenomenon has been difficult to explain and one can only make speculations without going into a very detailed investigation. One assumption examined was that release of phosphorus through leaf decomposition could account for the difference in phosphorus concentrations relative to flow, between the main channel and secondary streams. However, this theory proved unlikely as a vegetation map showed a consistent distribution of tree types (hardwood stands being dominant, intermingled with mixed stands and softwood stands) for all the watersheds in the study area.

The end of an algal bloom and its subsequent decomposition could also contribute to fluctuations in phosphorus concentrations. However, intensive monitoring of phosphorus concentration would be necessary to interpret these fluctuations properly.

The results indicate that the watersheds directly contributing runoff to the main channel (i.e. stream from William to Thomas and from Thomas to Fletcher) may be more saturated with respect

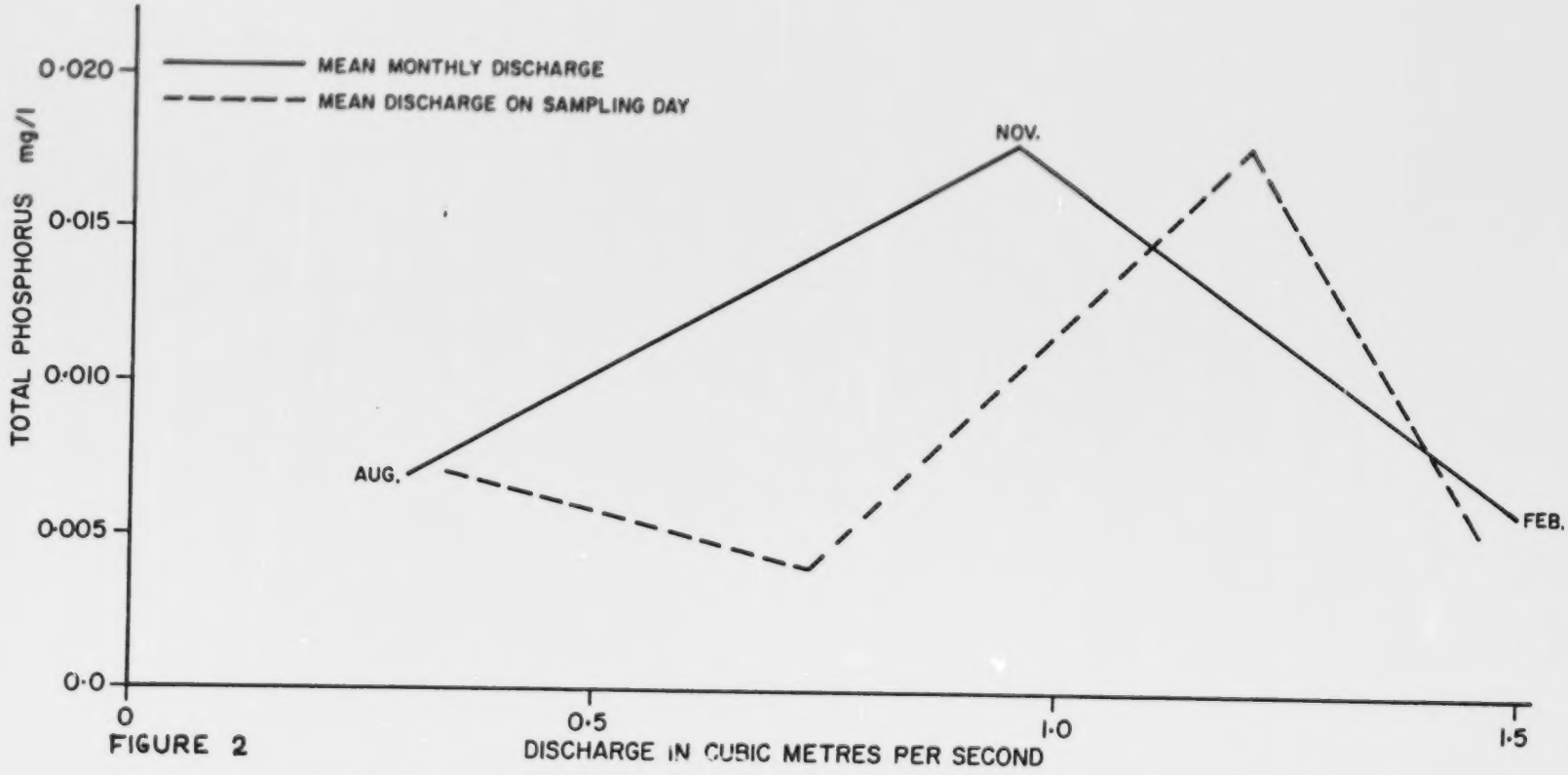

FIGURE 2

PHOSPHATE CONCENTRATION VS. MEAN FLOW IN STREAM BETWEEN POWDERMILL AND WILLIAM

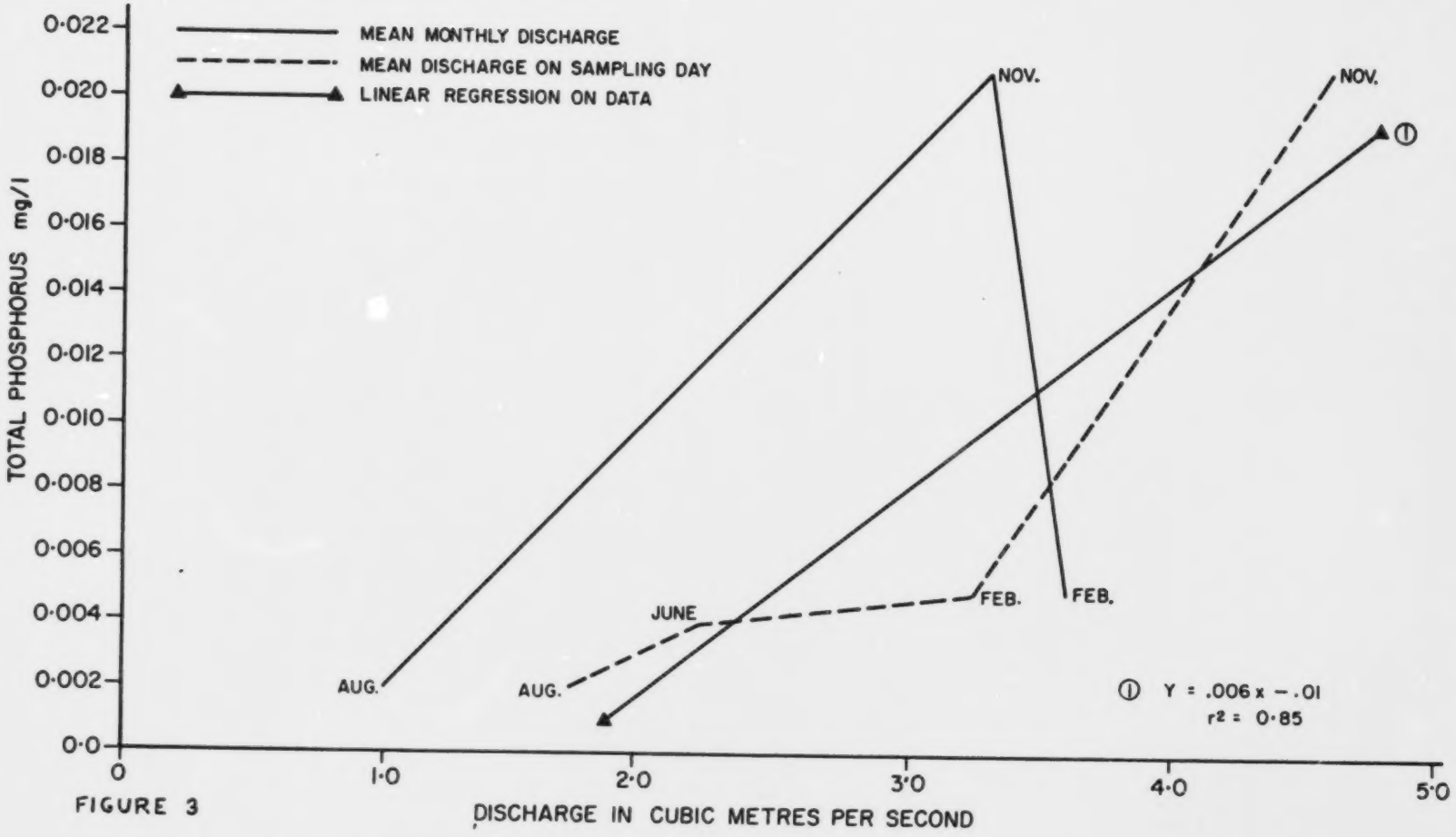

FIGURE 3

PHOSPHATE CONCENTRATION VS. MEAN FLOW IN STREAM BETWEEN WILLIAM AND THOMAS

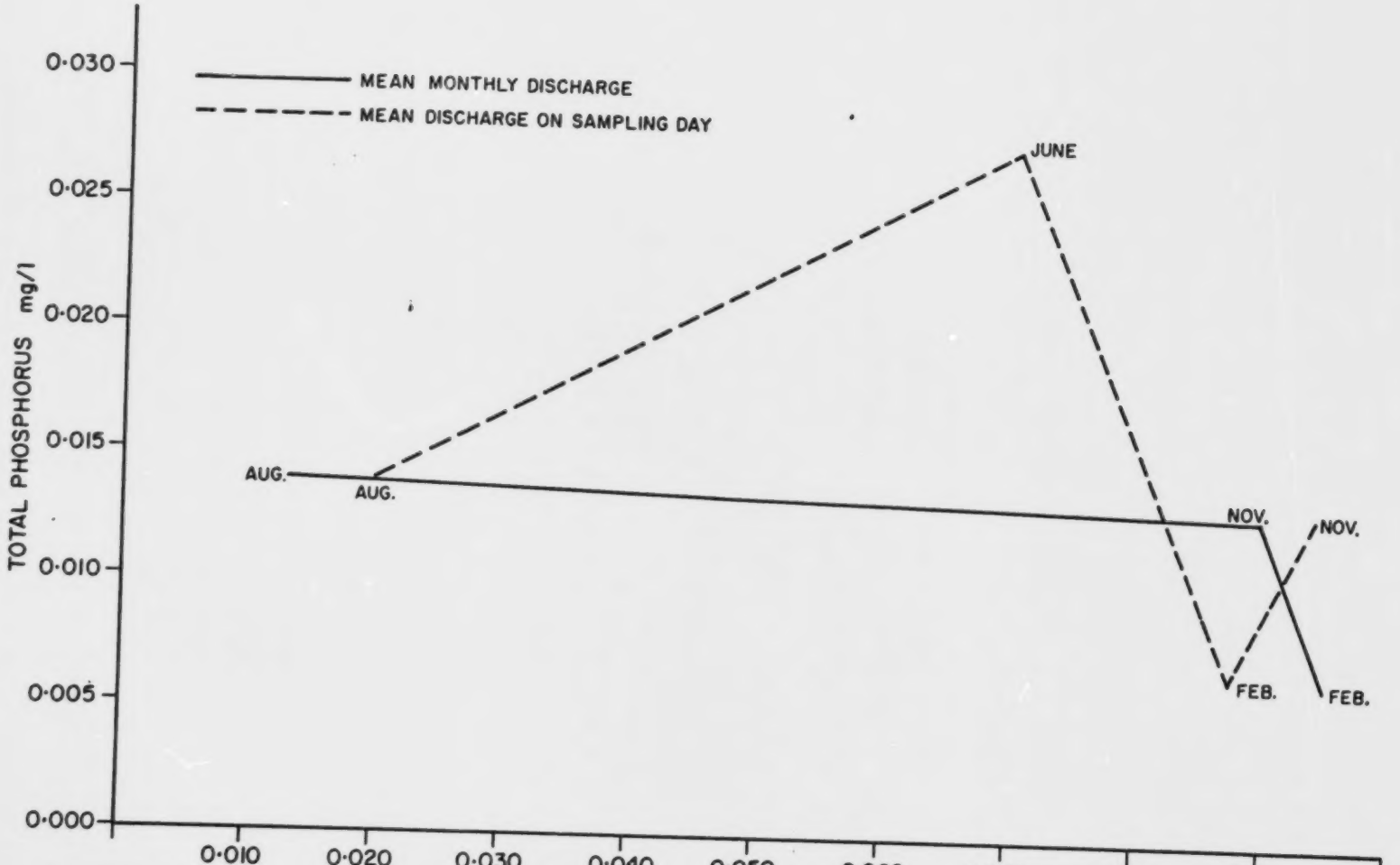

FIGURE 4

PHOSPHATE CONCENTRATION VS. MEAN FLOW IN MUDDY CREEK

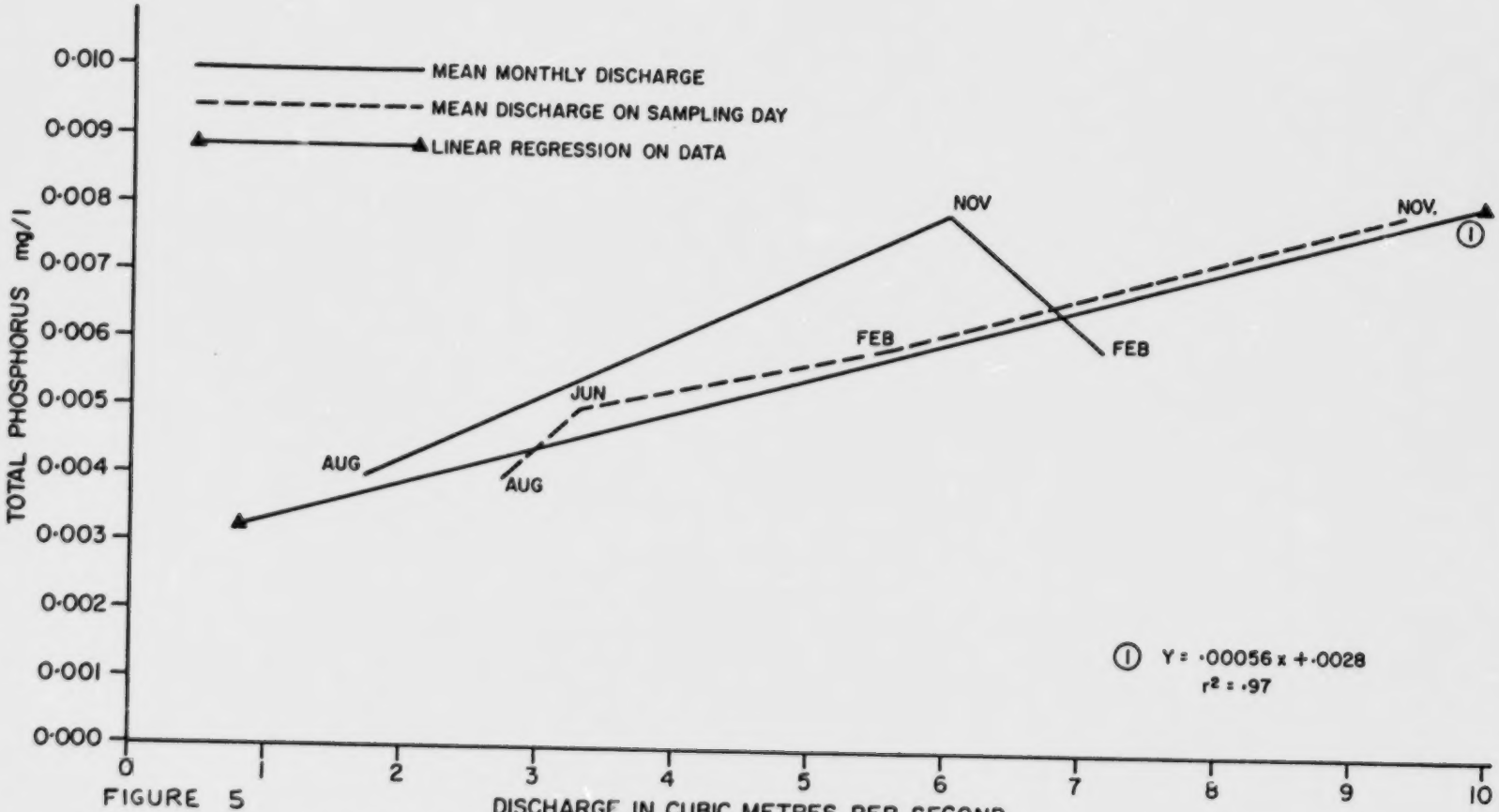

FIGURE 5

PHOSPHATE CONCENTRATION VS. MEAN FLOW IN STREAM BETWEEN THOMAS AND FLETCHER

to anthropogenic phosphorus. Consequently, more phosphorus may be lost to the flowing waters during periods of high runoff. More investigations are necessary to confirm these findings.

Oxygen Content of Lakes

The oxygen content was influenced by temperature stratification in all study lakes. This is evident from the isopleths for oxygen saturation (Figures 6-11). Third Lake, Three Mile Lake and Muddy Pond showed a hypolimnetic oxygen deficiency of up to 70% less than saturation. However, all lakes were above the threshold of 10% oxygen saturation, when a variety of chemical and biological processes begin to display adverse effects (Chapra and Dobson, 1981).

The rapid flushing rate of Fletcher Lake (35 time per annum) kept oxygen saturation greater than 75% during the entire study period.

Lakes Powder Mill and Thomas showed hypolimnetic oxygen deficits to as low as 10% saturation during the summer months.

A Thienemann trophic index based on volumetric oxygen depletion rates in the hypolimnion was calculated for lakes Powder Mill, Thomas and Third. The Thienemann index was employed to provide an alternate trophic status evaluation to that of the OECD phosphorus model, as chlorophyll concentrations were not determined to evaluate photosynthetic productivity during the study.

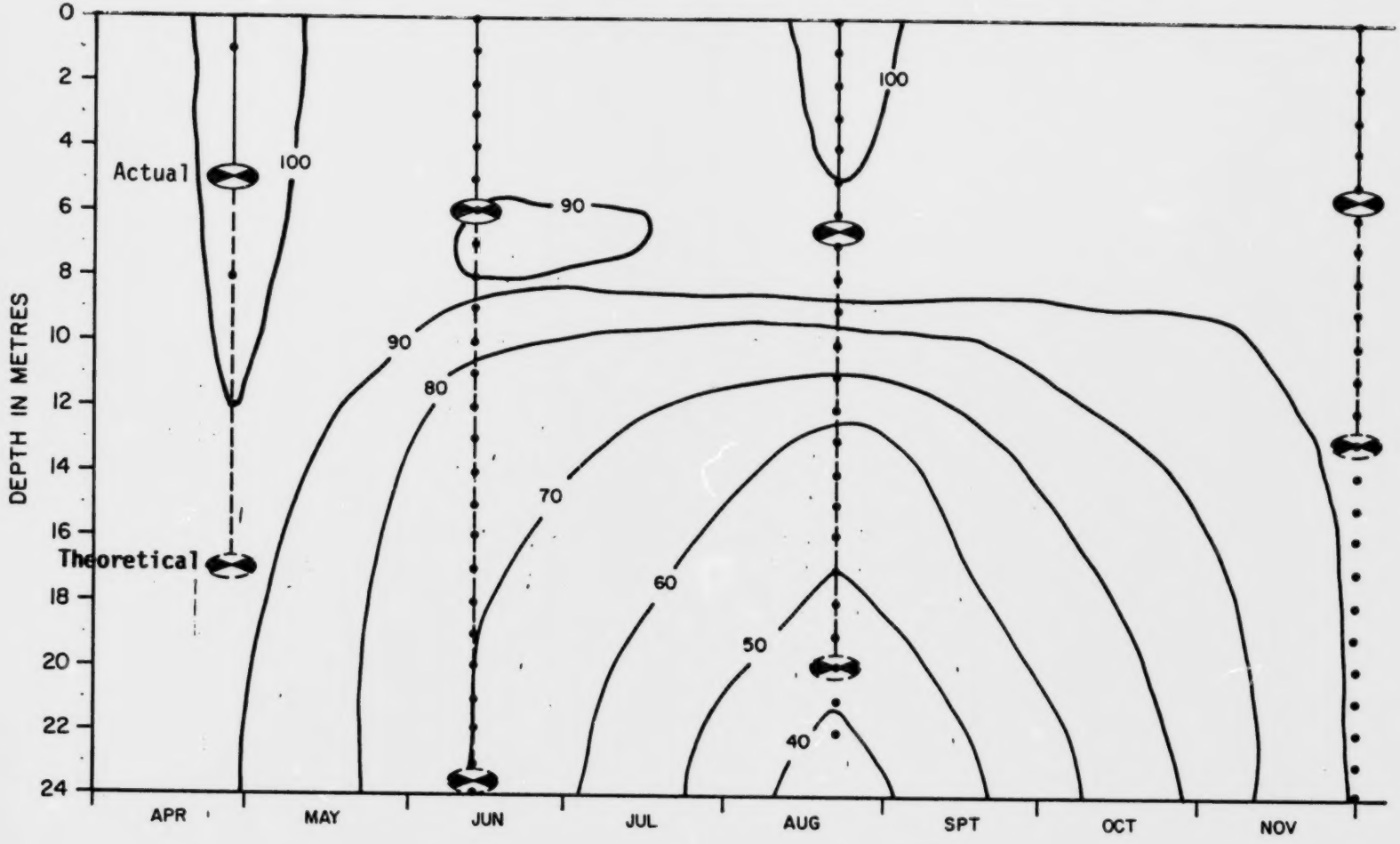

FIGURE 6 THIRD LAKE 1983, ISOPLETHS FOR % OXYGEN SATURATION AND ACTUAL AND THEORETICAL SECCHI READING

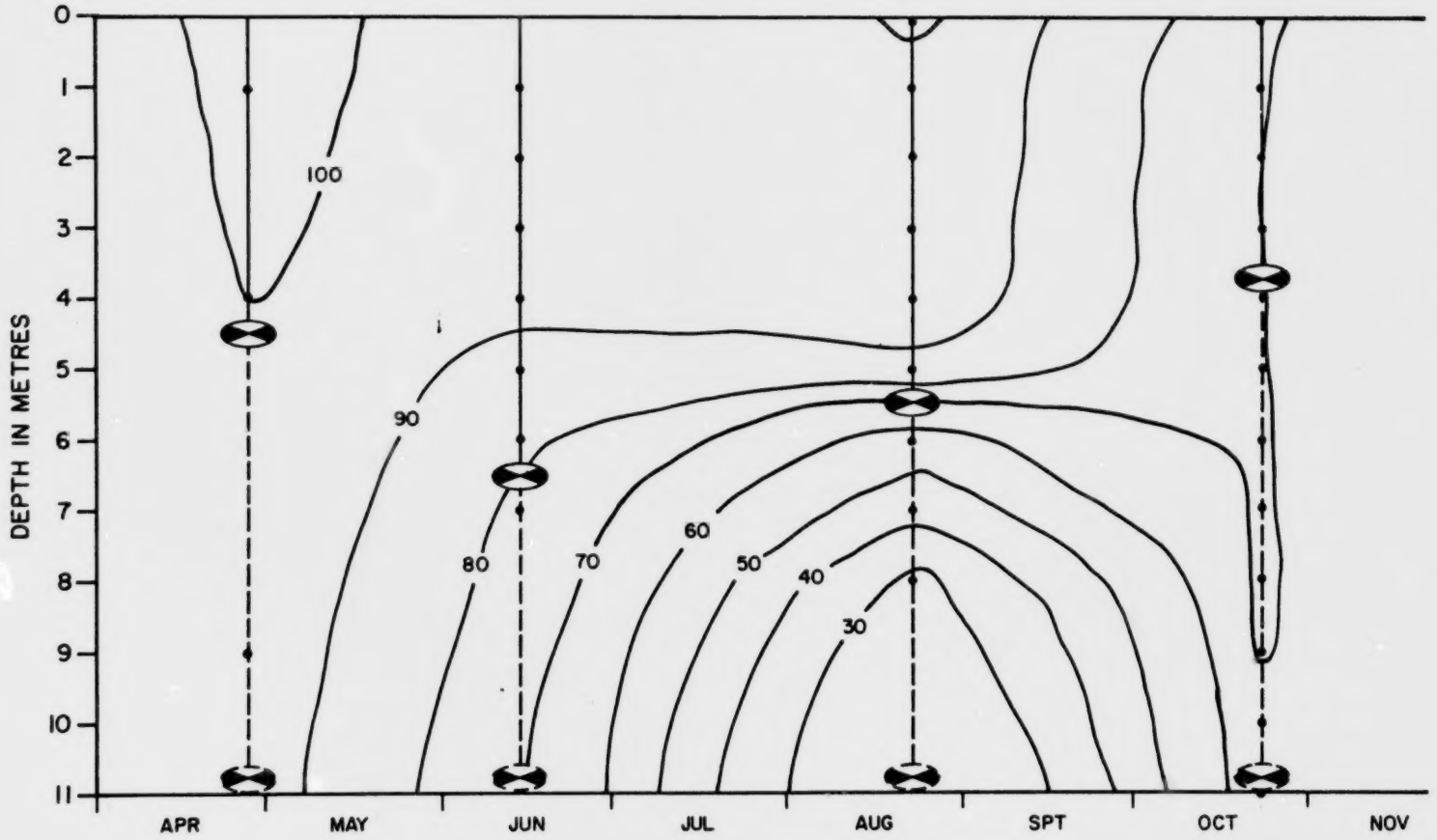

FIGURE 7 THREE MILE LAKE 1983, ISOPLETHS FOR % OXYGEN SATURATION AND ACTUAL AND THEORETICAL SECCHI READING

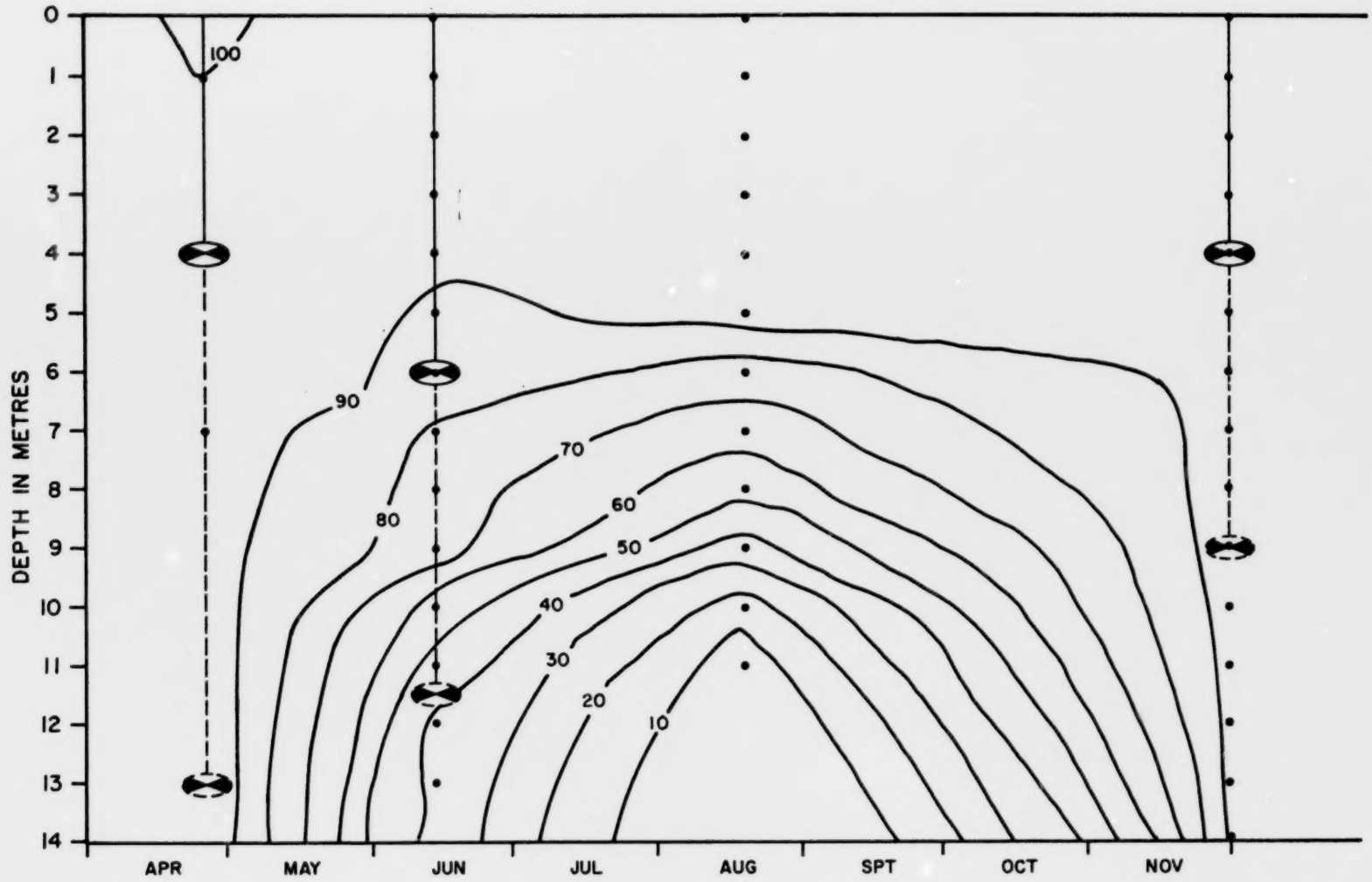

FIGURE 8 POWDER MILL LAKE 1983, ISOPLETHS FOR % OXYGEN SATURATION AND ACTUAL AND THEORETICAL SECCHI READING

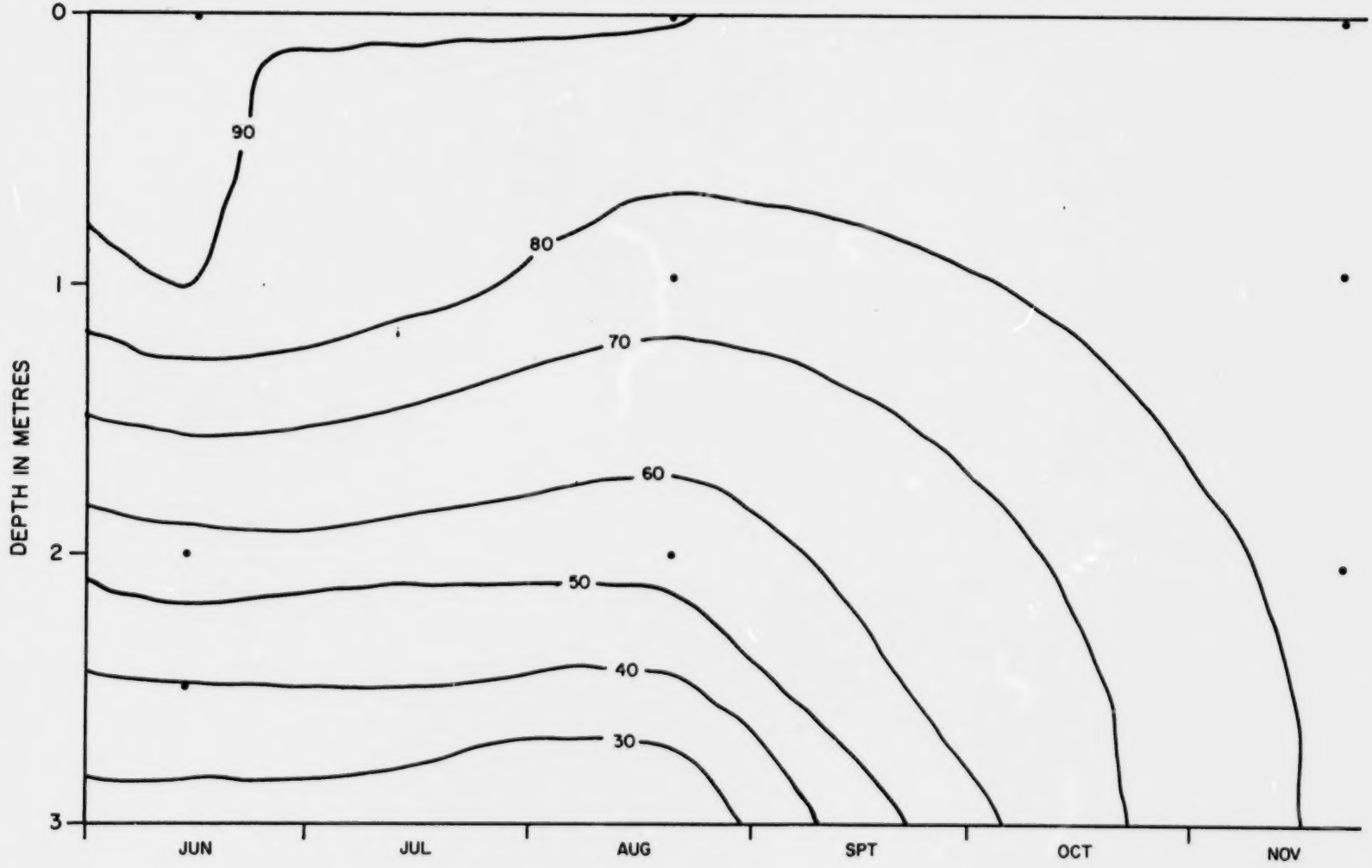

FIGURE 9 MUDDY POND 1983, ISOPLETHS FOR % OXYGEN SATURATION AND ACTUAL AND THEORETICAL SECCHI READING

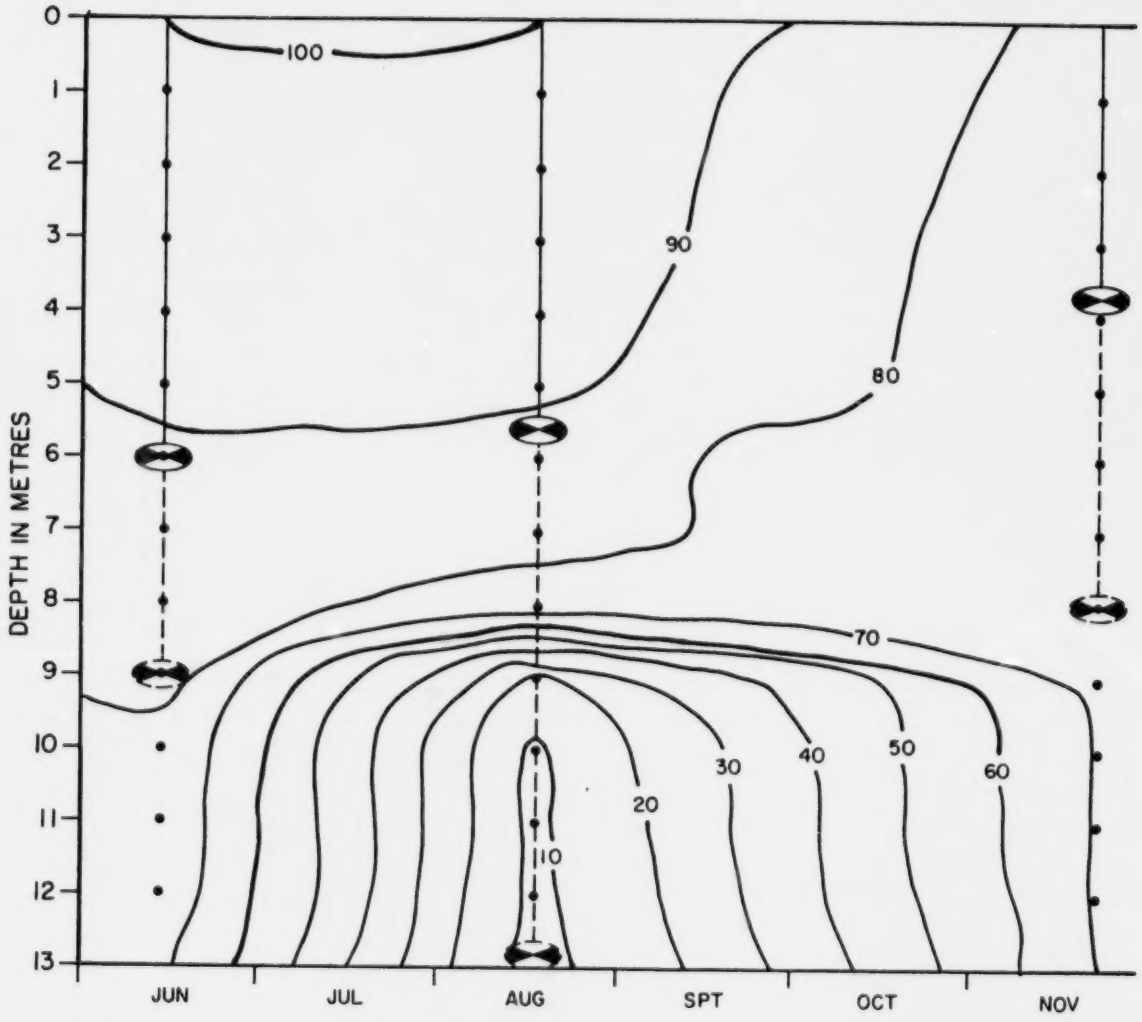

FIGURE 10 LAKE THOMAS 1983, ISOPLETHS FOR % OXYGEN SATURATION AND ACTUAL AND THEORETICAL SECCHI READING

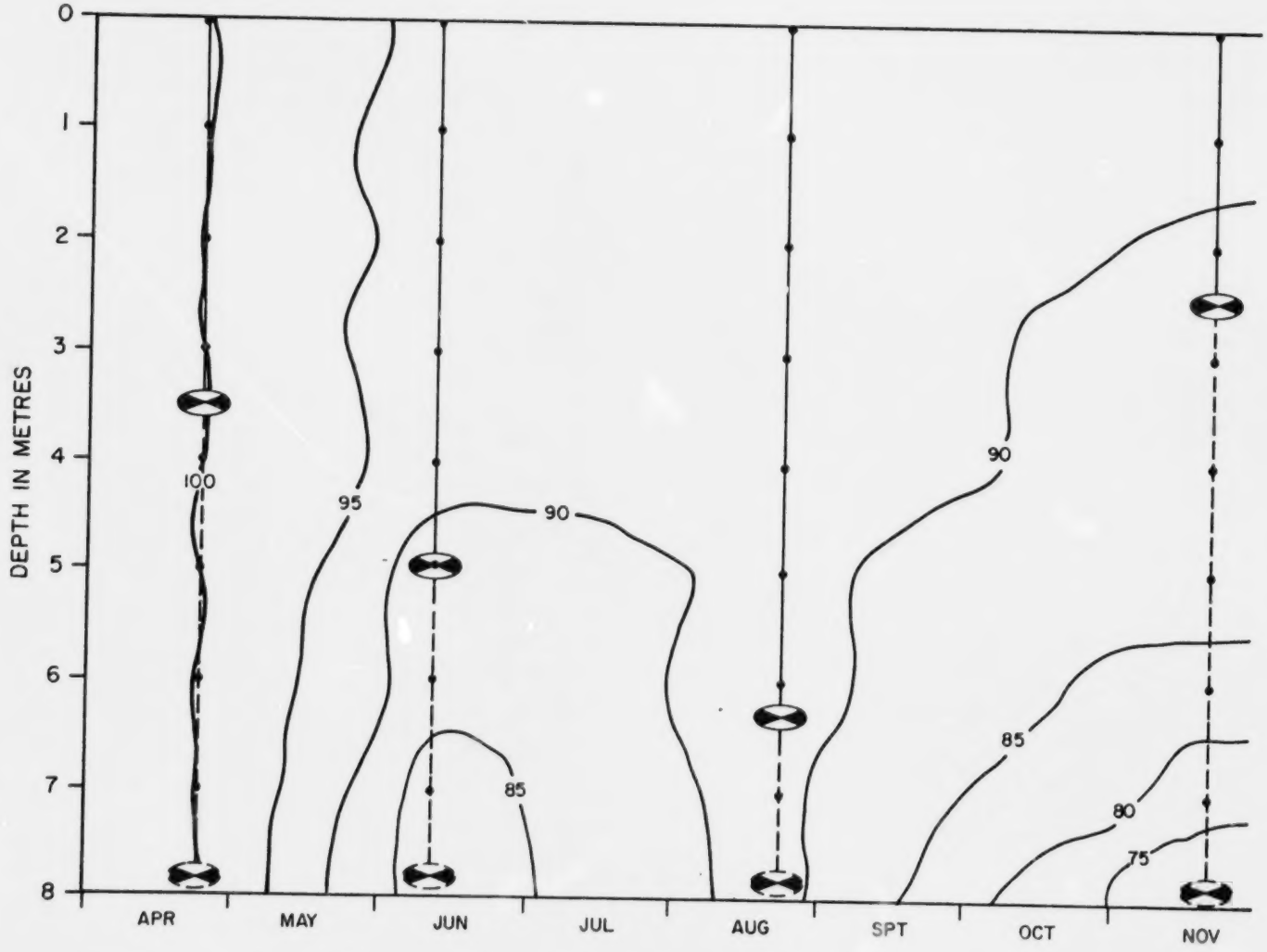

FIGURE 11 FLETCHER LAKE 1983, ISOPLETHS FOR % OXYGEN SATURATION AND ACTUAL AND THEORETICAL SECCHI READING

Thienemann Classification of Lake Trophic Status

Thienemann classification of lake trophic status is based on the oxygen depletion rate in the hypolimnion, initial oxygen concentration at spring turnover and the duration of thermal stratification.

The Thienemann index was calculated for lakes Powder Mill and Thomas, which both showed low concentrations of hypolimnetic oxygen during mid-summer. Third Lake was included for comparative purposes.

The Thienemann index, TI_T can be expressed as:

$$TI_T = 11.1 \left[\frac{Dv\ t_s}{C_i} \right] \qquad (2)$$

where Dv is the volumetric oxygen depletion rate expressed in $mg.L^{-1}$ per month, t_s is the duration of the stratified period in months, and C_i is the oxygen concentration at the onset of stratification expressed in $mg.L^{-1}$ (Chapra and Dobson, 1981). A Thienemann index between 0 and 5 indicates oligotrophy, between 5 and 10 mesotrophy and above 10 eutrophy.

The duration of thermal stratification in the lakes was estimated at five months. The sampling schedule did not permit a more precise delineation of autumn turnover in the study lakes.

According to Thienemann index both Third and Powder Mill Lakes are considered mesotrophic and Lake Thomas eutrophic, its

Thienemann index being similar to that calculated for Central Lake Erie (Chapra and Dobson, 1981).

The classification of the study lakes by the Thienemann index placed the lakes in a higher trophic status than the OEC phosphorus classification. This difference could be generated by the over-estimation of the stratification period for the study lakes.

Primary production in the study lakes was not estimated. However, it would be possible to relate the oxygen depletion in the hypolimnion to carbon fixation in the epilimnion (Chapra and Dobson, 1981).

Transparency of Lakes

In order to determine the magnitude of light penetration in the study lakes, transparency was measured with a Secchi disc in all but two lakes: in Muddy Pond the disc was visible to the bottom of the pond and Perry Lake was sampled only from the shore.

Actual and theoretical Secchi depths are presented in Figures 6, 7, 8, 9, 10 and 11. Theoretical Secchi depths were obtained by transposing point locations on the OECD phosphorus curves to the OECD Secchi probability curves. Then theoretical Secchi depths were interpolated from the abcissal axis on the OECD Secchi figure.

Mean annual Secchi depths were calculated from the four readings taken at each lake during the study period, except for Lakes

Table 4. Nova Scotia and Great Lakes Data Relevant to Oxygen Depletion along with Calculated Values of the Thienemann Index

Lake or Basin	Thickness of Hypolimnion (m)	Volumetric Oxygen Depletion ($mg.L^{-1}$ per month)	Initial Oxygen Concentration ($mg.L^{-1}$)	Duration* of Stratification (mo)	Thienemann** Index TI_T
Third	15	1.3	12	5*	6.0
Powder Mill	5	1.46	11	5*	7.4
Thomas	5	2.6	11*	5*	13.1
Superior	134	0.14	13	3.5	0.4
Huron	50	0.24	13	3.5	0.8
Central Erie	3.9	3.2	11	4.0	12.9
Eastern Erie	14.7	1.73	12	4.5	7.2
Ontario	71	0.33	13	4.5	1.3

* Estimated

** 0 - 5 oligotrophic
5 - 10 mesotrophic
10+ eutrophic

Powder Mill and Thomas where only three readings were taken. The average was then used to classify each lake based on OECD Secchi disc transparency.

The average Secchi depth for study lakes was 5 m, which was greater than the 3 m average found for a study of 288 lakes in the province (Underwood, 1984). However, actual Secchi depths were always less than the theoretical depths.

According to Secchi disc transparency all study lakes were classified mesotrophic. Low mean annual Secchi depths were attributed to the fact that they were measured during spring and fall turnover, when lake mixing and high runoff rendered the lakes more turbid than at other times of the year (Mudroch, 1984).

DISCUSSION

Comparison of Trophic Indices Used and Discussion of the Condition of Lakes

The classification of the trophic status of the studied lakes was based on three parameters: mean annual phosphorus concentrations; Secchi disc transparencies; and hypolimnetic oxygen depletion.

The results of the classifications are shown in Table 5.

The classification of trophic status of the lakes based on Secchi disc transparency and oxygen depletion is similar but results

Table 5. Comparison of Trophic Classifications Based on Phosphorus, Secchi and Oxygen

Lake Name	OECD Trophic Classification Based on Phosporus	OECD Trophic Classification Based on Secchi	Trophic Classification Based on Thienemann's Oxygen Index
Muddy Pond	Ultra-oligotrophic	Mesotrophic	Mesotrophic
Three Mile	Oligotrophic	Mesotrophic	
Powder Mill	Oligotrophic	Mesotrophic	Mesotrophic
Perry	Oligotrophic	N/A	
Muddy Pond	Mesotrophic	N/A	
Thomas	Oligotrophic	Mesotrophic	Eutrophic
Fletcher	Oligotrophic	Mesotrophic	

in higher levels of eutrophy than the classification based on phosphorus concentrations. Secchi depth was obtained in two of the four sampling times during spring and fall turnover, when turbidity could be greater due to lake mixing and increased runoff.

The correct estimation of the stratification period is extremely important for the calculation of the Thienemann index. A Thienemann index calculated for Third Lake assuming a stratification period of three months would be 3.6 in comparison with an index of 6.0 that resulted from the use of five months. Consequently, Third Lake

would be classified as oligotrophic if a shorter stratification period better represented actual conditions.

In 1979, Hart undertook an environmental assessment of the surface waters of five lakes (all presently under review of this study), in the vicinity of the proposed Cobequid Industrial Park near Third Lake. This study provided some contemporary baseline data, as well as analyzed possible effects which the proposed development would have on the surface waters in the area. Sampling was carried out in the spring, a time when phosphorus concentrations have been linked to the rate of algal growth during the following summer (Vollenweider and Kerekes, 1980). Phosphorus concentrations in three of the five lakes Hart studied were similar to those found in this study. Hart concluded that surface waters in the area were of high quality.

If there were concerns that sewage sysems were contributing significantly to the nutrient budget of the lake, one would expect some relationship between phosphorus and nitrogen, as both are abundant in sewage waters (Vallentyne, 1974). Table 1 demonstrates that a greater variation exists for mean annual phosphorus concentrations than for nitrogen. Thus it is concluded that there is little evidence of phosphorus input through sewage systems. However, Hart et al. (1978) have suggested that intense development and population growth in the region of the headwater lakes would result in increases in production of domestic sewage wastes. They expressed

concerns that such development would render the headwater lakes less viable as a water supply and for recreational use. This concern is in apparent contrast to our results. However, our data base is sparse and it would be appropriate to supplement the information with a more thorough examination of the lakes. In addition an examination of changes in population density should be conducted.

Effects of Further Phosphorus Loading

An attempt was made to determine the increase in phosphorus loading that would put the lakes in the next level of eutrophy. Results of these calculations are shown in Table 7. The $[\overline{P}]$ that would hypothetically put the lake in the next order of eutrophy was chosen to be the minimum value provided in the proposed boundary values for trophic categories based on total phosphorus probability curves. These values are shown in Table 6.

The ratio between calculated Es_c that would put the lakes in the next trophic level and the Es_c for the existing trophic level, ranged from 1.1 for Third Lake to 2.8 for Lake Fletcher and Muddy Pond. With this technique Lake Thomas is seen to be the most sensitive oligotrophic lake to further phosphorus loading, and Lake Fletcher the least. However, despite its relative sensitivity, Lake

Table 6. Proposed Boundary Values for Trophic Categories

Trophic Category	$[\overline{P}]$ in $mg.m^{-3}$
Ultra-oligotrophic	<4
Oligotrophic	4-16
Mesotrophic	16-50
Eutrophic	50-150
Hypertrophic	>100 (from Vollenweider and Kerekes, 1980)

Table 7. An Estimation of Phosphorus Input from Watersheds that Would Be Required to Increase Lake Trophic Status by One Level

Lake	Existing $[\overline{P}]$ ($mg.m^{-3}$)	$[\overline{P}]$ for Next Trophic Level ($mg.m^{-3}$)	Ratio	Es_c for Next Trophic Level ($mg.m^{-2}$)	Mass, Based on Es_c & Ad_c ($mg \times 10^6$)
Third	3.5 (ulta oligo)	4 (oligo)	1.1	18.2	16
Three Mile	7.0	17	2.4	7.4	50
Powder Mill	6.5	17	2.6	37.4	605
Muddy Pond	18.0	51	2.8	59.6	50
Thomas	8.0	17	2.1	17.4	1150
Fletcher	6.0	17	2.8	18.8	1700

Thomas could absorb an estimated increase of 1150 kg of phosphorus annually before reaching a mesotrophic stage. Lake Fletcher could conceivably assimilate an additional 1170 kg annually before productivity would be sufficient to classify it as mesotrophic.

Although the lakes do not indicate any serious signs of eutrophy based on phosphorus concentrations, one should stress the fact that some of the study lakes (i.e. Thomas and Powder Mill lakes) already display hypolimnetic oxygen deficiencies during the summer months. Further studies should be conducted to delineate the period and extent of oxygen depletion in these lakes, to confirm the differences between oxygen and phosphorus productivity indices.

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GEOCHEMISTRY OF BOTTOM SEDIMENTS IN THE SHUBENACADIE RIVER HEADWATER LAKES

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INTRODUCTION

Surface sediments were collected from 20 Shubenacadie River headwater lakes during a comprehensive investigation of the Shubenacadie-Stewiacke River Basin carried out jointly by the federal government agencies and Nova Scotia Department of Environment in 1977 (Mudroch and Sandilands, 1978). Chemical analyses of the surface sediment samples indicated contamination by As and Hg in the Waverley area. To investigate the extent of the contamination, sediment cores were obtained from selected stations in Lakes Powder Mill, Thomas, Fletcher and Williams in fall 1977. The results have shown that the sediment consisted of two layers. The surface layer in each of the cores was enriched in Pb, Cu, Zn and Co but particularly in As and Hg. It was concluded that this enrichment was caused by cultural loadings, due to the disturbance of gold mining wastes and development of past mining areas.

In the present study we investigated the contamination of the sediments from Muddy Pond and Three Mile Lake and the relationship among As, Hg and Au in the sediments from Lakes Thomas and Powder Mill. Sediment sampling was carried out by a recently developed equipment suitable for sampling of very fine grained soft sediment. Surface sediments were also collected in Lakes Loon and Perry which belong to the Shubenacadie River Basin and were not sampled during the survey in 1977.

MATERIALS AND METHODS

The sediment was sampled by a lightweight corer (Williams and Pashley, 1979) at the deepest points in Muddy Pond, Lake Thomas, Powder Mill Lake and Three Mile Lake. Each core was visually inspected, extruded and subdivided into 1 cm sections for chemical analyses. These subsamples were freeze dried and ground to 149 μm size. The determination of major elements (Si, Al, Fe, Ca, Mg, Na, K, Mn, P and S) and metals (Cu, Cr, Pb, Zn, Ni and Co) was carried out by the X-ray fluorescence spectrometry: organic matter was determined by heating at 550°C for 3 hours; As and Au were determined by neutron activation and Hg was determined by the method described by Inland Waters Directorate, Water Quality Branch (1979). Surface sediments were obtained at the deepest point in Loon Lake and near the outlet in Perry Lake. Both sediment samples were prepared and analyzed by the same method as the core subsamples.

RESULTS AND DISCUSSION

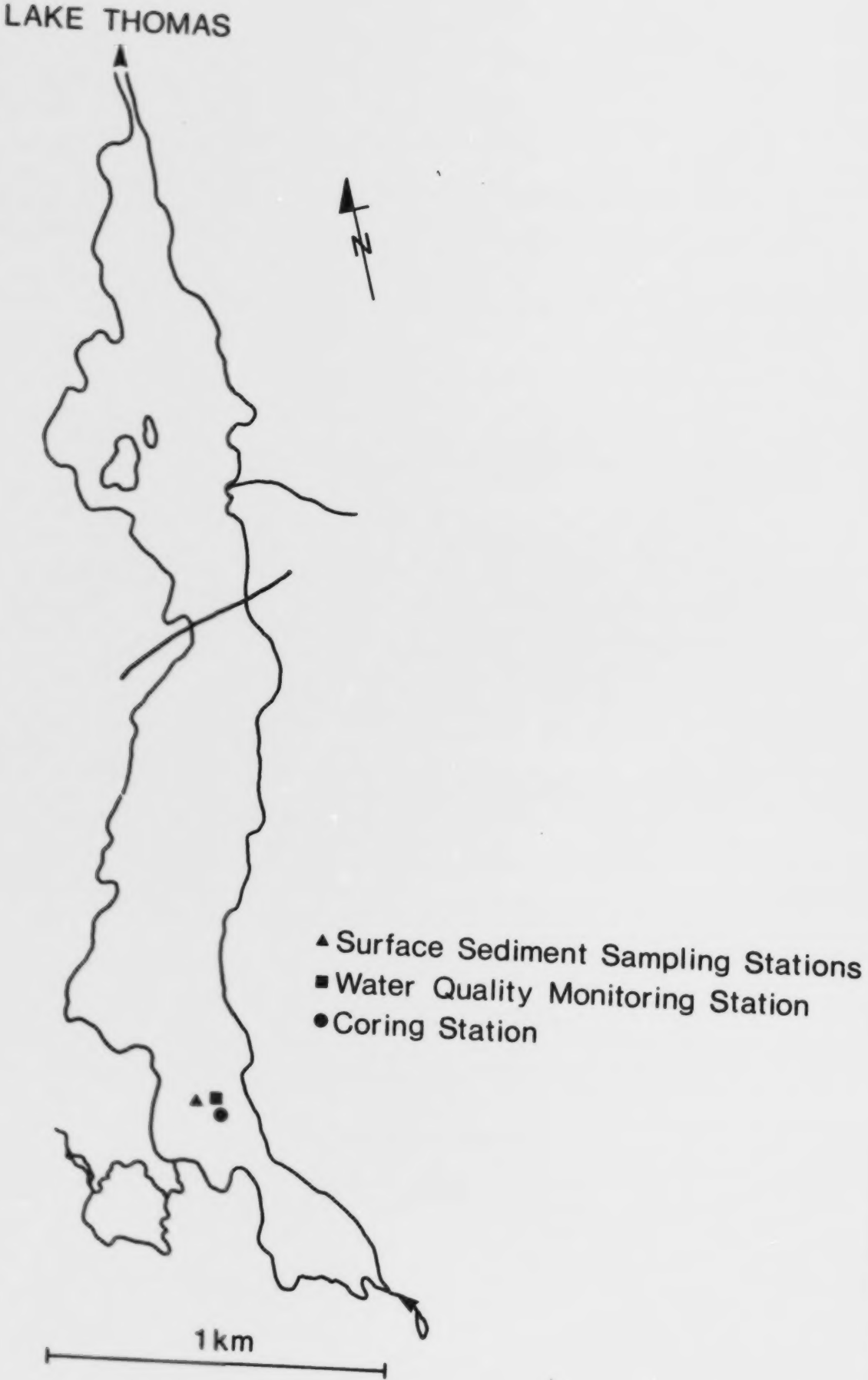
Concentrations of As and Hg in surface sediment from Lakes Loon and Perry are shown in Table 1. They may be considered as background concentrations of these two elements in the basin.

The sediments from all investigated lakes consisted of soft silty clay. The entire sediment column (50 cm) from Muddy Pond was dark brown underlain by peat. The surface sediments from Powder Mill

Table 1. Concentration of As, Au and Hg in Lakes Perry and Loon sediments

Lake	As $ug.g^{-1}$	Au $ug.g^{-1}$	Hg $ug.g^{-1}$
Perry	4	2	0.30
Loon	43	3	0.70

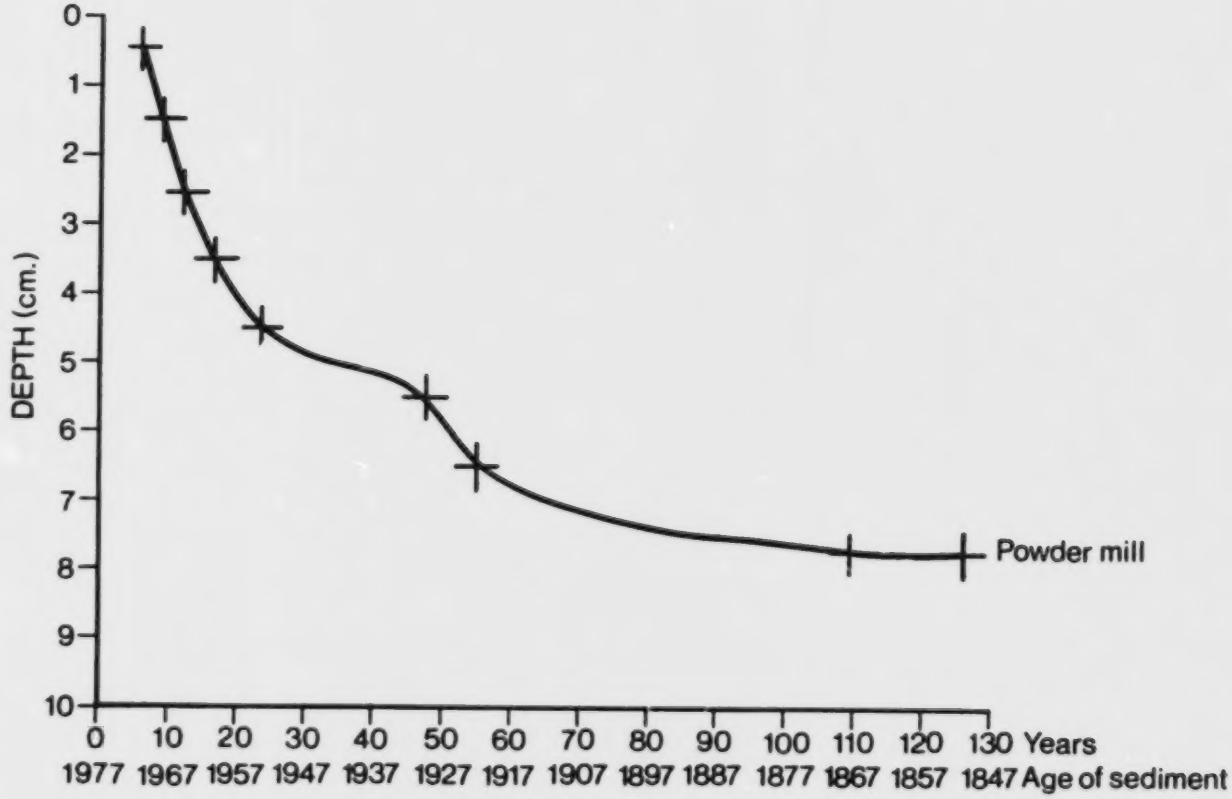
Lake and Lake Thomas were light brownish grey silty clay underlain by dark brown sediment of similar consistency. The surface layers were about 8 cm and 20 cm thick in Powder Mill Lake and Lake Thomas, respectively. Similar surface layers were observed during the 1977 sediment sampling (Mudroch and Sandiland, 1978). It was concluded that these layers originated from the disposal of gold mining waste from the milling of the gold bearing ore. However, the layer extended down only to a 8 cm depth in the core obtained from Lake Thomas in 1977. The reason for the different thickness of the layer was obviously the sampling location. In 1977 the core was taken about 0.5 km south of the deepest point. The sediment core obtained during the 1983 study was collected at the deepest point in Lake Thomas (Figure 1) so that different sedimentation rates and variation of the sediment composition could be expected. Only the topmost 2 cm sediment had a slightly different colour than the rest of the core collected at the deepest point in Third Lake.


LAKE THOMAS
N
▲ Surface Sediment Sampling Stations
■ Water Quality Monitoring Station
● Coring Station
1 km

Concentrations of major elements in light brownish grey surface sediment layers indicated the different sources of material deposited in Lakes Powder Mill and Thomas. The dating of the sediment in Powder Mill Lake showed that the surface 7 cm of the sediment accumulated during the past 60 years. On the other hand it took about 60 years for accumulation of the sediment layer between 7 and 8 cm depth (Figure 2). The dating indicated an increased sediment input which most likely originated by construction activities in the lake drainage basin during the past 60 years. The differences in the geochemistry between the surface sediment layer and the rest of the sediments in Lakes Powder Mill and Three Mile are shown in Table 2. This finding confirms the results obtained during the 1977 study of the Shubenacadie River headwater lakes.

The major difference between the two sediment layers was the content of organic matter. The surface layer in Powder Mill Lake contained a higher concentration of inorganic material. The underlain sediment, rich in organic material, was typical of the environment before the start of the development in the drainage basin. Such sediment was found in the Three Mile Lake where only the topmost 2 cm layer of sediment was different from the rest of the sediment column (Table 2). The changes of the topmost sediment composition probably reflect recent disturbances in the Three Mile Lake's basin, i.e. road or homes construction.

The concentration profiles of Au, As, Hg and S in the sediments from Muddy Pond, Powder Mill Lake and Lake Thomas are


DEPTH (cm.)
0
1
2
3
4
5
6
7
8
9
10
Powder mill
0 10 20 30 40 50 60 70 80 90 100 110 120 130 Years
1977 1967 1957 1947 1937 1927 1917 1907 1897 1887 1877 1867 1857 1847 Age of sediment

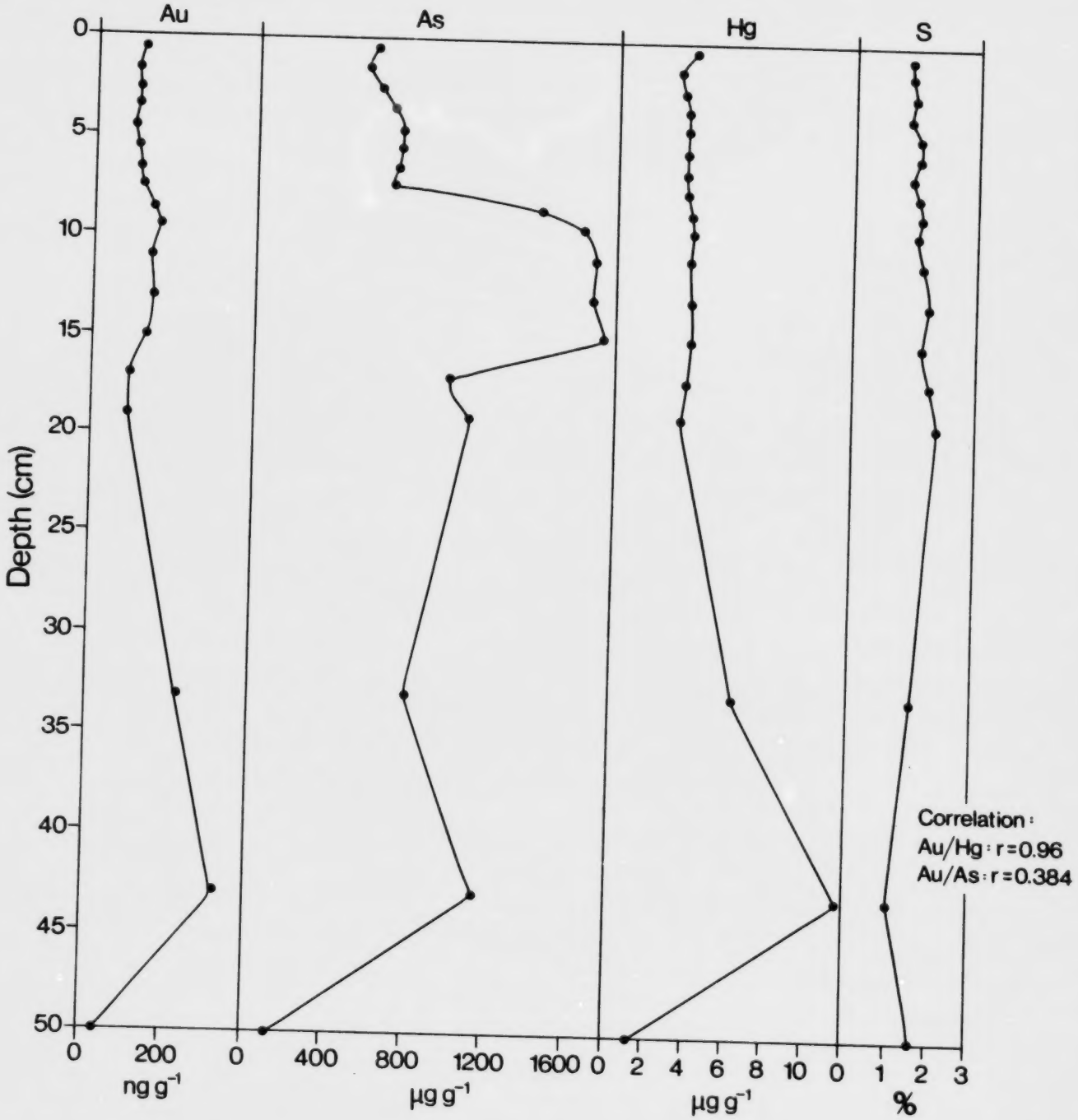
presented in Figures 3 to 5. The highest concentration of As (1750 $\mu g.g^{-1}$) was found at the 10 to 15 cm sediment depth in the core obtained from the middle of the Muddy Pond. This finding is not surprising since Muddy Pond served as a tailing pond for the Waverley gold mines during the 19th century and at the beginning of the 20th century. The concentration of As in the surface sediment collected from various areas in Muddy Pond were up to 6196 $\mu g.g^{-1}$ (Trip and Skilton, this report).

The highest concentrations of Au and Hg in the sediment collected from Muddy Pond were at about 42 cm sediment depth. There was a positive relationship between the concentration of these two metals in the core (correlation coefficient 0.96, no. of samples 18). A similar relationship was observed between Hg and Au in the Powder Mill Lake sediment. The concentration of Hg was highest in Powder Mill Lake compared to all four sampled lakes.

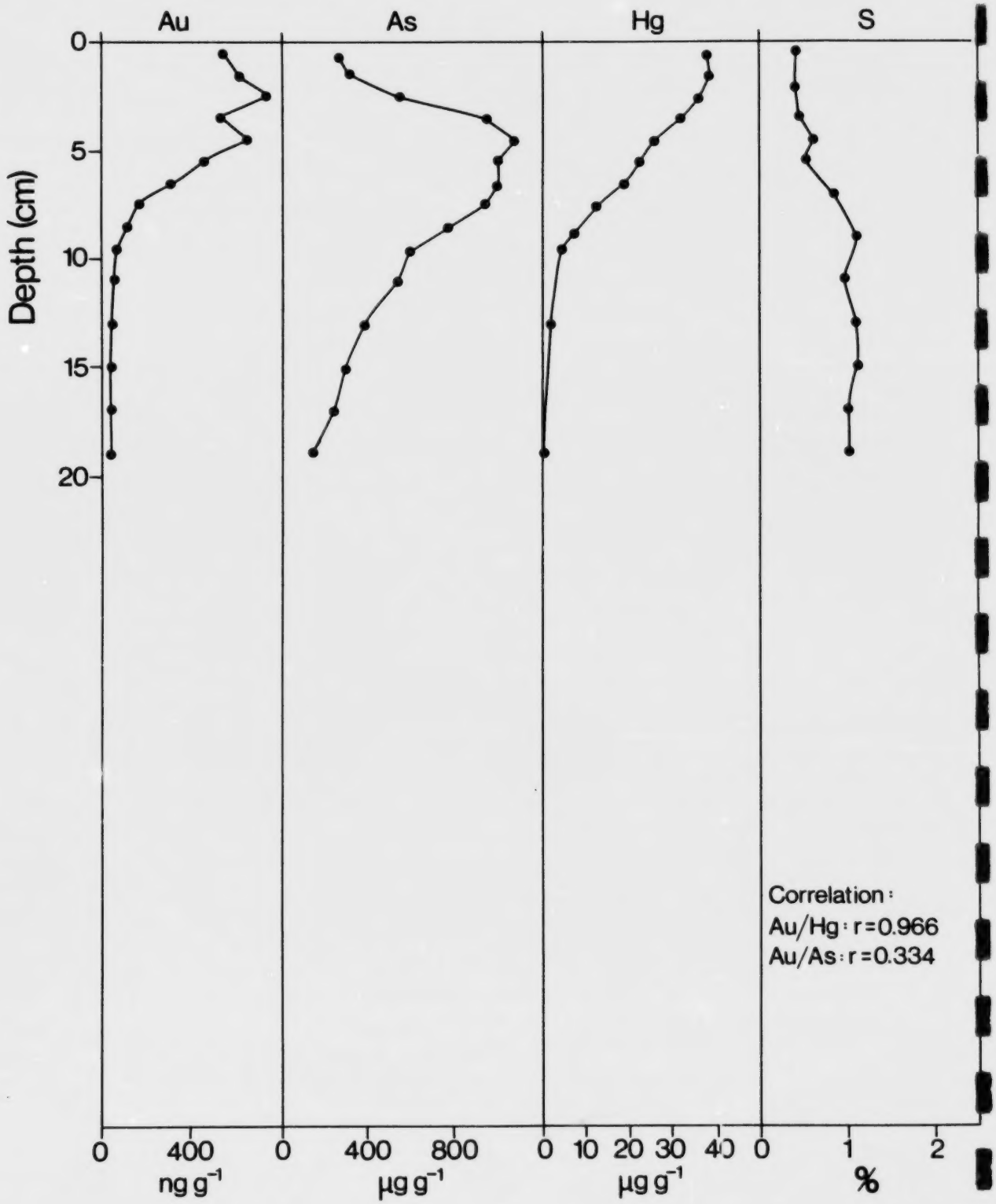
In Powder Mill Lake sediment, the highest concentration of As was between 3 and 8 cm depth and decreased towards the sediment surface. On the other hand, the concentration of Hg was highest at the sediment surface and declined sharply at 8 cm depth. There were still significant differences between the Hg concentration at 9 cm and 20 cm depth (Figure 4).

The concentration profiles of As and Hg and the relationship between Hg and Au indicated that these contaminants originated from different sources in the Powder Mill Lake basin. Mercury and gold originated most likely from the amalgamation process associated with

Concentration profiles of Au, As, Hg, and S in Muddy Pond sediment.



Concentration profiles of Au, As, Hg, and S in Powder Mill Lake sediment.



the gold extraction. On the other hand, arsenic originated from the milling wastes and mine waste rock, which was used often in the area for construction of roads and railway beds. The exposure of these wastes to weathering resulted in release of arsenic into surrounding environment. However, the concentration of Hg (40 $\mu g.g^{-1}$) in the surface sediment indicated either a continuing input of material containing Hg into the Powder Mill Lake or an upward migration of this metal through the sediment pore water.

The highest concentration of Au (950 $ng.g^{-1}$) was found at 13 cm sediment depth in Lake Thomas (Figure 5). The relationship between Hg and Au was not as significant as in Muddy Pond and Powder Mill Lake sediments. It is possible that the main source of Hg and Au in these two lakes were the wastes from the gold refining by Hg amalgamation. However, Lake Thomas could have received some material from the mill tailings located on its shore. These mill tailings contained great quantities of As (Trip and Skilton, this report).

No relationship was observed between As, Hg or Au and S in all sampled sediments. The concentration of S was an order of magnitude higher than that of As. Consequently, it was impossible to determine if the As in the sediment is associated with arsenopyrite.

Concentrations of metals in sediment core from Lake Thomas are shown in Table 3. The concentraion of Pb was consistent from the surface to 14 cm depth in the core ranging between 240 and 270 $\mu g.g^{-1}$ and increased below 14 cm to 310 $\mu g.g^{-1}$. Concentrations of Cr, Co and Zn were similar to all depths with mean values 145 $\mu g.g^{-1}$, 30 $\mu g.g^{-1}$

Table 3. Concentrations of metals in Lake Thomas sediment ($ug.g^{-1}$)

Depth cm	Cr	Co	Cu	Zn	Ni	Pb
0- 2	148	30	42	320	27	263
2- 3	135	39	38	320	28	254
3- 4	147	39	37	312	28	240
4- 5	153	42	36	310	28	243
6- 7	139	31	41	316	28	244
7- 8	140	41	36	322	26	238
8- 9	147	40	37	320	27	244
10-12	146	37	34	296	13	248
12-14	128	29	37	273	13	272
16-18	132	31	26	315	12	307
18-20	122	39	17	293	13	305
24-26	131	31	20	310	12	310

and 305 $\mu g.g^{-1}$, respectively. The concentration of Cu and Ni decreased below 12 cm depth from 42 to 20 $\mu g.g^{-1}$ and 28 to 13 $\mu g.g^{-1}$, respectively.

Concentrations of Cr, Co, Zn, Cu, Ni and Pb did not change in the 50 cm sediment column in Muddy Pond. Mean values for these metals were 90, 41, 365, 5, 23 and 215 $\mu g.g^{-1}$, respectively.

Concentrations of all investigated metals decreased at the 8 cm depth in the sediment from Powder Mill Lake. The concentration of

Cr decreased from 135 to 65 $\mu g.g^{-1}$, Co from 45 to 10 $\mu g.g^{-1}$, Cu from 29 to <1 $\mu g.g^{-1}$, Zn from 270 to 110 $\mu g.g^{-1}$, Ni from 23 to 12 $\mu g.g^{-1}$ and Pb from 310 to 44 $\mu g.g^{-1}$. The lower values represent the background concentrations.

Increased concentration of Pb (up to 515 $\mu g.g^{-1}$), and Zn (up to 290 $\mu g.g^{-1}$) was found in the surface 2 cm sediment in Three Mile Lake. Below 3 cm the concentrations of Pb and Zn decreased to 42 $\mu g.g^{-1}$ and 190 $\mu g.g^{-1}$, respectively, and remained similar throughout the rest of the core. The other metals investigated were found in similar concentrations throughout the entire sediment column. Mean concentration of As was 25 $\mu g.g^{-1}$, Hg 0.35 $\mu g.g^{-1}$, Cr 685 $\mu g.g^{-1}$, Co 28 $\mu g.g^{-1}$, Cu <1 $\mu g.g^{-1}$ and Ni 35 $\mu g.g^{-1}$.

Elevated metal concentrations in Lakes Powder Mill and Three Mile coincided with the occurrence and extent of the light brownish grey surface sediment layer. Concentrations of metals in Lake Thomas followed a different pattern than those of As and Hg in Lakes Powder Mill and Three Mile.

The investigation showed that activities in the drainage basin affect the sedimentation rates and the sediment geochemistry in each of the lakes. The past gold mining activities generated large amounts of wastes containing As, Hg and other metals. These wastes are located in different areas of the Shubenacadie River headwater lakes drainage basin (Trip and Skilton, this report). The waste material was disturbed by erosion and perhaps used as construction material during the recent development of the basin. The loosened

waste material was further carried by streams and runoff into the lakes where it settled to the bottom. The sediment deposited before the development of the basin consisted mainly of autochtonous material with a high concentration of organic matter. The sedimentation rates were lower than at present and the settling particles originated mainly from the primary production in these oligotrophic lakes. The sediment geochemistry has changed particularly in the lakes receiving great quantities of the waste material. In addition, the lakes are connected by streams which contribute to the transport of material from one lake to the other. Consequently, the disturbance in the drainage basin of one lake may affect the other lakes downstream in the system.

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TRANSPORT OF CONTAMINANTS BY STREAMS CONNECTING SHUBENACADIE RIVER HEADWATER LAKES

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INTRODUCTION

There is enough scientific evidence to show that contaminants such as metals and organics, which enter an aquatic ecosystem, get associated with suspended solids and bottom sediments. However, some of the sediment-associated contaminants may be solubilized under changing conditions of pH and oxidation-reduction (redox) potential. The solubilized contaminants can be further transported within the lake by currents, carried out of the lake by streams or can be adsorbed on particles suspended in the water column. In the Shubenacadie headwater system the transport of contaminants from one lake to the other by water or suspended particles becomes very important because all headwater lakes are connected by streams. The particles transported from one lake to the other can either settle to the bottom or can be carried by the current into the next downstream lake. Consequently, the contaminants originating in the drainage basin of one lake are spread over the entire downstream system.

In order to obtain information on the transport of As, Hg and other metals originating from the past gold mining activities through the Shubenacadie River headwater lakes, suspended solids were sampled from the following connecting streams (Fig. 1):

Three Mile Lake to Powder Mill Lake

Powder Mill Lake to Lake William

Lake William to Lake Thomas

Little Lake
Shubenacadie River
Lewis Lake
Bennery Brook
Fish Lake
Grand Lake
Bennery Lake
Halifax International Airport
Beaverbank Lake
Lake Fletcher
Johnson River
Fenerty Lake
Kinsac Lake
Soldier Lake
Springfield Lake
Lake Thomas (north)
Perry Lake
Miller Lake
Third Lake
Lake Thomas (south)
Three Mile Lake
Second Lake
Muddy Pond
WAVERLEY
First Lake
Powder Mill Lake
Lake William
Rocky Lake
Lake Charles
Loon Lake
Cobequid Bay
Minas Channel
Halifax
Study Area
Nova Scotia
N
0 1000 2000 3000
metres

Lake Thomas to Lake Fletcher

Muddy Pond to Lake Thomas

MATERIALS AND METHODS

Water was sampled from the connecting streams in April, June, August and November, 1983. Suspended solids were sampled in April, August and November, 1983. About 3,000 L of water were pumped from each creek and processed through a Westphalia continuous flow separator at a speed of 4 $L.min^{-1}$. Collected particles were freeze dried, weighted, homogenized and used for geochemical analyses. The concentration of As was determined by the neutron activation, Hg by cold vapor technique and organic matter by loss on ignition at 550°C for three hours. Concentrations of major elements (Si, Al, Ca, Mg, K, Na, Fe, Mn, Ti and P) and metals (Pb, Zn, Cu, Ni, Cr, Co and V) were determined by X-ray fluorescence spectrometry. Precision and accuracy of the method was discussed by Mudroch (1984).

Two computer programs were used to predict the distribution of chemical species in lake water. PHREEQE is a Fortran IV computer program designed to model geochemical reactions. The details of the calculation by this program were described by Parkhurst et al. (1980). The computer program GEOCHEM was developed for the calculation of chemical equilibria in soil solutions and other natural water systems. The details of the computation and application of the program were discussed by Mattigod and Sposito (1979).

RESULTS AND DISCUSSION

Concentrations of suspended solids in the connecting streams in April, August and November 1983 are shown in Table 1. Concentrations of major elements, metals and organic matter in suspended solids are shown in Table 2. Concentrations of major elements, metals and organic matter in the surface 0-1 cm sediment of the lake are given in Table 3.

The concentration of Si was lower in suspended solids than in the bottom sediments. The results indicated that the resuspended sediments consisting of less dense and smaller particles such as organic matter and alumino-silicates were carried out of the lakes by the creeks whereas the larger and heavier particles such as silica grains remained. The concentration of Al was similar in both suspended solids in the creeks and bottom sediments. The lowest concentration of Al in suspended solids were in August. Al represents the inorganic material such as alumino-silicate minerals in sediments and suspended solids. Decrease of Al during August was due to the increase of particulate organic matter in the lake water and its further transport by the connecting creeks. Concentrations of Al and organic matter indicated that suspended solids collected in April and November included more resuspended bottom sediment particles from the lakes and soil particles from the erosion during the spring and fall runoff.

Table 1. Concentration of suspended solids in creeks ($mg.L^{-1}$)

	April	August	November
Three Mile Lake to Powder Mill	n.s.	0.30	1.00
Powder Mill to Williams	1.10	0.27	1.20
L. Williams to Thomas	1.20	0.72	0.65
L. Thomas to Fletcher	1.00	0.80	1.30
Muddy Pond to L. Thomas	1.30	0.90	1.90

With the exception of the creek connecting Muddy Pond with Lake Thomas, the concentration of organic matter in suspended solids was significantly higher than the surface sediments in each of the corresponding upstream lakes. However, the concentration of organic matter was similar in all three suspended solid samples collected from Muddy Pond Creek and with that of the Muddy Pond surface sediment. Generally, the concentration of organic matter in the suspended solids collected from the other four creeks was highest in August following the increase of the primary production in the lakes during the summer months.

One of the most significant differences in the composition of suspended solids was the concentration of Mn, which was an order of magnitude higher in all suspended solids than in the surface sediments. The concentration of Mn in all suspended solids increased up to nine times in August samples (Table 2). The increase in Mn

Table 2. Concentration of major elements and metals in suspended solids

Stream	Month	%										μg·g^{-1}						
		SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	Organic Matter	Cr	Co	Cu	Zn	V	Ni	Pb
Three Mile Lake to Powder Mill L.	April	Not sampled																	
	August	40.6	8.7	23.7	1.4	6.0	3.3	2.5	0.65	11.9	1.16	40.8	290	74	38	667	102	53	482
	November	48.2	13.1	21.0	1.5	2.7	1.4	3.2	0.84	7.2	0.91	39.2	178	62	71	504	125	43	466
Powder Mill Lake to Williams	April	49.5	12.4	17.5	1.6	5.4	4.8	3.7	0.70	2.7	1.69	59.1	299	46	76	773	87	54	686
	August	48.5	6.9	14.4	1.4	9.0	4.9	2.7	0.41	9.6	2.19	66.1	197	33	9	246	75	58	202
	November	59.1	12.6	16.0	1.5	1.9	1.4	3.2	0.82	2.9	0.61	33.0	178	53	39	334	108	33	369
L. Williams to L. Thomas	April	63.6	10.5	11.9	1.6	3.1	3.3	3.6	0.76	1.6	0.93	36.8	363	37	79	772	112	59	707
	August	58.2	7.2	13.9	0.9	5.1	3.2	1.7	0.56	7.5	1.72	59.5	395	31	282	1039	79	55	638
	November	48.2	6.5	19.2	1.4	5.9	1.9	1.7	0.65	13.6	1.05	46.7	397	49	124	757	156	57	584
L. Thomas to L. Fletcher	April	54.3	17.1	17.6	1.5	1.7	1.4	3.0	0.95	1.7	0.78	39.6	370	82	71	484	146	72	412
	August	47.3	9.9	17.7	1.1	4.0	2.2	2.2	0.68	14.1	0.92	51.5	526	57	110	1617	94	56	581
	November	50.7	20.0	17.7	2.2	0.9	1.1	4.1	1.19	1.7	0.38	24.1	270	55	83	349	174	51	468
Muddy Pond to L. Thomas	April	64.4	10.5	11.3	1.5	3.4	3.5	2.9	0.52	1.2	0.81	42.9	336	22	39	432	69	58	609
	August	47.0	9.1	18.5	3.4	9.2	1.6	2.6	0.79	7.2	0.72	40.8	539	47	141	1336	94	76	4961
	November	51.4	12.2	17.7	1.4	4.4	1.4	3.5	0.56	6.8	0.62	41.9	171	40	39	663	98	48	442

Table 3. Concentration of major elements and metals in bottom sediments (0-1 cm)

Lake	%											$\mu g \cdot g^{-1}$					
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	Organic Matter	Cr	Co	Cu	Zn	V	Ni	Pb
Three Mile	76.6	10.1	8.1	0.8	0.9	0.4	1.3	0.45	0.71	0.48	34.6	109	43	1	290	76	17	515
Powder Mill	63.3	16.5	17.6	1.5	0.6	0.4	3.9	0.59	0.23	0.47	19.1	130	45	28	265	98	21	320
Williams	67.2	9.0	10.7	1.2	0.7	0.5	1.8	0.45	0.54	0.31	13.9	n.d.	n.d.	36	246	n.d.	30	170
Thomas	64.8	17.2	9.1	2.4	0.4	0.9	3.8	0.83	0.21	0.28	10.3	148	30	42	320	120	27	263
Muddy Pond	72.2	11.7	8.5	1.2	1.4	0.5	3.3	0.57	0.24	0.40	43.1	96	42	1	190	65	23	202

n.d. = not determined.

concentration followed the changes in the concentration of dissolved oxygen (DO) in the lake water, in particular in the hypolimnion during the summer lake stratification. The concentrations of DO and dissolved Mn and Fe in the bottom water of the lakes are shown in Table 4. With decreasing concentration of DO dissolved Mn and Fe significantly increased in the bottom water in all lakes and only slightly in the creeks connecting Three Mile Lake with Powder Mill Lake and Muddy Pond with Lake Thomas. However, the changes in dissolved Mn and Fe concentrations were small in the oxygenated surface lake water. These results indicated dissolution of Mn and Fe from the bottom sediments during the anoxic conditions in the summer. The dissolved Mn was further transported upward by migration and currents into the oxygenated water where it precipitated. This particulate Mn was carried into the streams and contributed to the Mn concentration of the suspended solids.

The concentration of Fe in suspended solids from the streams connecting Lake Thomas with Lake Fletcher and Powder Mill Lake with Lake William was similar during all three sampling times. On the other hand, the concentration of particulate Fe was higher in August and November in the stream connecting Muddy Pond with Lake Thomas and in November in the stream connecting Lake William with Lake Thomas. It is possible that the dissolved Fe in the bottom water was absorbed on some of the resuspended heavier inorganic particles which then settled on the lake bottom. In the shallow Muddy Pond some of these particles with adsorbed Fe were carried out by the currents into the

Table 4. Concentration of dissolved O_2, Fe and Mn in bottom water and outflowing creeks

Lake	Month	Dissolved O_2	Fe ($mg.L^{-1}$)		Mn ($mg.L^{-1}$)	
			Lake	Outflowing Creek	Lake	Outflowing Creek
Three Mile	April	12.1	0.050	0.050	0.02	0.03
	June	9.2	0.050	0.110	0.03	0.09
	August	3.0	0.140	0.280	0.50	0.13
	November	8.7	0.120	0.120	0.03	0.03
	February	n.d.	n.d.	0.090	n.d.	0.07
Powder Mill	April	11.0	0.045	0.038	0.01	0.01
	June	4.2	0.070	0.038	0.12	0.02
	August	0.5	0.540	0.036	0.94	0.02
	November	12.0	0.140	0.19	0.03	0.04
	February	n.d	n.d.	0.08	n.d.	0.03
Thomas	April	11.5	0.060	0.070	0.03	0.07
	June	8.0	0.060	0.080	0.05	0.09
	August	1.0	0.140	0.110	1.30	0.07
	November	9.1	0.060	0.090	0.07	0.08
	February		n.d.	0.110	n.d.	0.11
Fletcher	April	11.4	0.100		0.06	
	June	8.3	0.070	n.d.	0.04	n.d.
	August	8.2	0.08		0.07	
	November	8.1	0.110		0.06	
	February	n.d.	n.d.		n.d.	
Muddy Pond	April	n.d.	0.080	0.100	0.05	0.05
	June	5.7	0.290	0.180	0.16	0.06
	August	5.3	0.420	0.250	0.17	0.08
	November	11.2	0.180	0.180	0.03	0.02
	February	n.d.	n.d.	0.07	n.d.	0.04
Third	April	12.0	0.020	n.d.	0.01	n.d.
	June	8.8	0.016	n.d.	0.01	n.d.
	August	4.5	0.120	n.d.	0.11	n.d.
	November	11.8	0.040	n.d.	0.02	n.d.

n.d. = not determined.

creek. However, more complicated mechanisms such as those suggested by Hem (1978) may be responsible for the dissolution/precipitation processes of Mn and Fe in the Shubenacadie lakes.

It is well known that dissolved Mn and Fe are unstable in oxygenated water and become rapidly oxidized and precipitated. Mn deposited in surface sediment layers is solubilized under reducing conditions prevailing in the bottom water/sediment pore water system. However, when redox potential is gradually lowered, Mn is solubilized more easily than Fe and is precipitated at a higher redox potential when following the gradient to more oxygenated conditions (Balzer, 1982). The concentrations of released Mn and Fe depend on concentrations and solid phase species in the sediment. Balzer (1982) found that the concentration of dissolved Fe under oxic and anoxic conditions is limited by the equilibrium with solid Fe phases (hydroxide and amorphous sulphide, respectively) and that bottom water enrichment in dissolved Mn originates from excess solid Mn within the top 3 cm of sediment. Eaton (1979) found about 20 times higher flux of Mn from anoxic sediments than from oxic sediments in Chesapeake Bay.

The results of this investigation indicate that the redox processes are responsible for the precipitation of Mn and transport of some metals through the Shubenacadie headwaters system. If the solid species of Fe and Mn would be $Fe(OH)_3$ and MnO_2 the redox potential would be between 1 and 8 pE at the bottom during the summer stratification in the investigated lakes. The mineralogical analyses of suspended solids by the X-ray diffraction did not show the presence of

Mn oxides. However, these oxides could be present in the amorphous form and, consequently, would not be detected. In addition, Mn may be adsorbed on the surface of Fe oxide or hydroxide particles. Computer programs PHREEQE and GEOCHEM were used to calculate the concentration of chemical species of dissolved Mn and Fe in the bottom water of Lake Thomas in August under different redox conditions. Results of the calculation are shown in Table 5. It can be seen that major chemical species of dissolved Mn remain at the same concentrations in the lake water at increasing pE values. On the other hand, with increasing pE

Table 5. Distribution of major chemical species of dissolved Mn an Fe in Lake Thomas water at various pE values

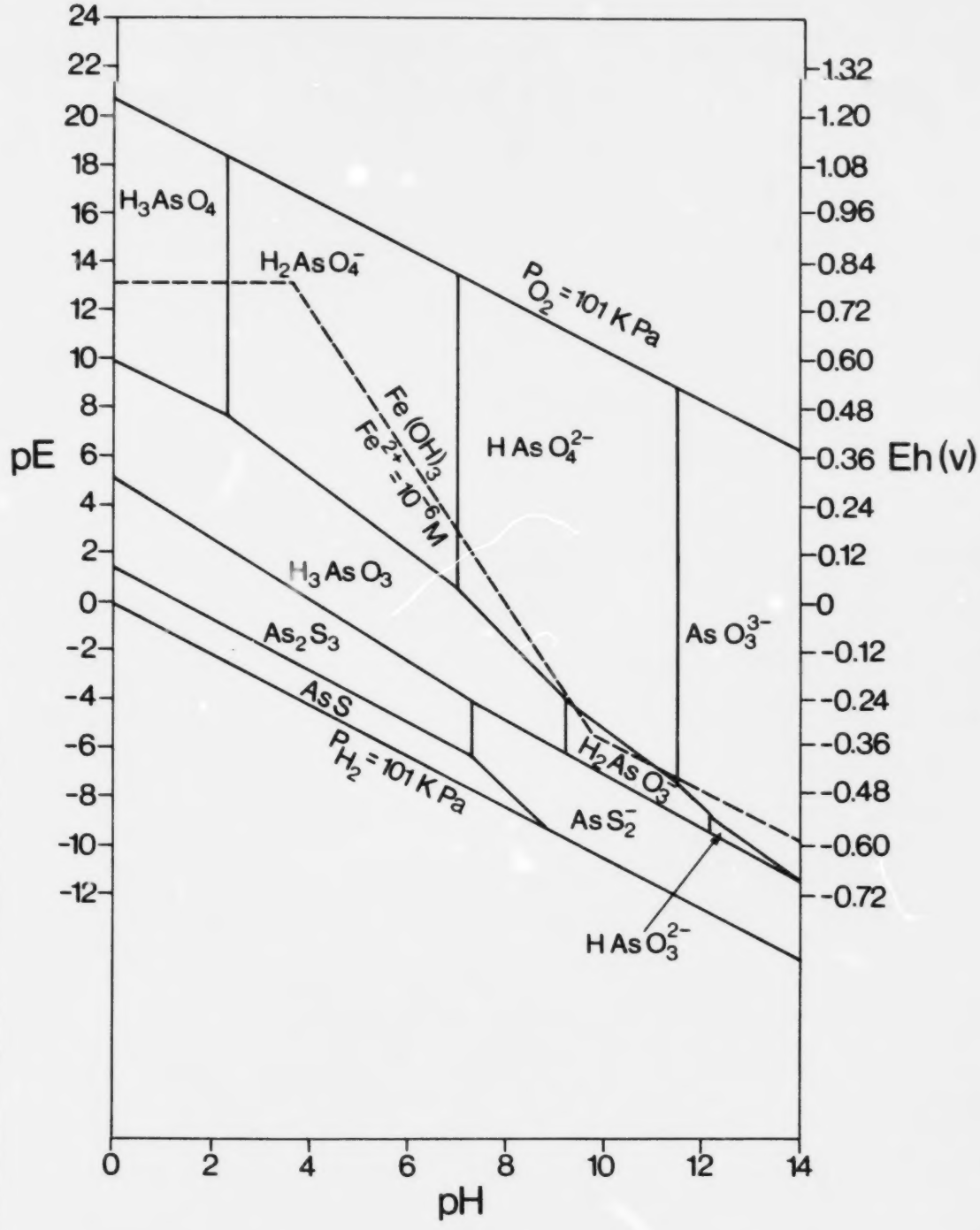
pE	Mn		Fe	
	Major Species	Concentration (molality)	Major Species	Concentration (molality)
2	$MnSO_4^\circ$	2.23×10^{-7}	$FeSO_4^\circ$	2.17×10^{-8}
	$MnCl^+$	5.91×10^{-8}		
	$MnHCO_3^+$	3.61×10^{-8}		
6	$MnSO_4^\circ$	2.23×10^{-7}	$FeOH_2^+$	4.69×10^{-7}
	$MnCl^+$	5.92×10^{-8}	$FeSO_4^\circ$	1.76×10^{-8}
	$MnHCO_3^+$	3.61×10^{-8}		
10	$MnSO_4^\circ$	2.23×10^{-7}	$FeOH_2^+$	2.46×10^{-6}
	$MnCl^+$	5.92×10^{-8}	$FeOH_3^\circ$	4.39×10^{-8}
	$MnHCO_3^+$	3.61×10^{-8}		
12	$MnSO_4^\circ$	2.23×10^{-7}	$FeOH_2^+$	2.46×10^{-6}
	$MnCl^+$	5.91×10^{-8}	$FeOH_3^\circ$	4.39×10^{-8}
	$MnHCO_3^+$	3.61×10^{-8}		

values, major chemical species of dissolved Fe changed from $FeSO_4^\circ$ to Fe-hydroxides. In addition, the computation showed that during the increase of the redox potential the bottom water of Lake Thomas becomes oversaturated with $Fe(OH)_3$ ($IAP/K_s = 1.35$, where IAP is the ion activity product and Ks the solubility product). Under these conditions Fe-hydroxide may precipitate and adsorb Mn and other metals dissolved in the lake water.

Under the above described redox conditions As would exist most likely as $H_2AsO_4^-$ in the lake water. However, the redox conditions are approaching those under which As(V) could change to more toxic As(III) species. The location of the pE-pH zone which can be expected in the hypolimnetic anoxic water in the summer is shown in Figure 2.

At present we have no knowledge about the solid species of Fe and Mn and the concentration of As(III) and As(V) in the sediments and water in the Shubenacadie Lakes. A detailed study both in the laboratory and in the field is needed to identify various Mn, Fe and As forms in the sediments and evaluate the effect of the redox changes on the As speciation in the water.

The concentrations of most of the investigated metals were higher in the suspended solids than in the lake sediments. The highest concentration of Zn was found in the creeks connecting Lake William with Lake Thomas during August 1983 (Table 2). An anomalously high concentration of Pb occurred in suspended solids in the creek connecting Muddy Pond with Lake Thomas. However, the increase of


pE
Eh (v)
pH
24
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
1.32
1.20
1.08
0.96
0.84
0.72
0.60
0.48
0.36
0.24
0.12
0
-0.12
-0.24
-0.36
-0.48
-0.60
-0.72
0
2
4
6
8
10
12
14
H_3AsO_4
$H_2AsO_4^-$
$P_{O_2} = 101\,KPa$
$Fe(OH)_3$
$Fe^{2+} = 10^{-6}\,M$
$HAsO_4^{2-}$
H_3AsO_3
As_2S_3
AsS
$P_{H_2} = 101\,KPa$
AsO_3^{3-}
$H_2AsO_3^-$
AsS_2^-
$HAsO_3^{2-}$

metal concentrations in the lake water was insignificant (Clair, this report). It is possible that metals originating by solubilization from the sediments during the summer anoxic conditions were immediately adsorbed by the suspended particles or freshly precipitated Fe-hydroxides and transported into the streams.

Concentrations of As and Hg in the suspended solids and surface sediments are given in Table 6. Generally, the concentration of As was higher in the suspended solids than in the lake sediments and increased from April to November. The highest concentration of As was in suspended solids and water sampled in April, August and November in the stream connecting Muddy Pond with Lake Thomas. The concentration of Hg was below detection limit (0.02 $\mu g.L^{-1}$) in all water samples collected from the creeks and was lower in all suspended solids than in the bottom sediments in April. However, it was higher in suspended solids than in the sediment in August in the creeks connecting Muddy Pond with Lake Thomas, Powder Mill Lake with Lake William and Three Mile Lake with Powder Mill Lake. The highest concentration of Hg was found in suspended solids transported from Muddy Pond into Lake Thomas in August. There was no relationship between the concentration of organic matter and Hg or As in suspended solids. However, a good relationship between Hg and As (correlation coefficient 0.914, n = 9) in suspended solids indicated that these two elements originated from the same source. The results further indicated that either the creeks carried particles with high concentrations of Hg and As or that As and Hg were solubilized from

Table 6. Concentration of As and Hg in suspended solids and surface sediments

	April		August		November	
	As $\mu g.g^{-1}$	Hg $\mu g.g^{-1}$	As $\mu g.g^{-1}$	Hg $\mu g.g^{-1}$	As $\mu g.g^{-1}$	Hg $\mu g.g^{-1}$
Lake Thomas to Lake Fletcher	248	0.78	247	0.78	352	0.71
L. Thomas (sediment)	143	9.50				
Lake William to Lake Thomas	275	0.74	129	0.46	490	1.02
Muddy Pond to Lake Thomas	681	3.47	1053	15.00	1818	6.20
Muddy Pond (sediment)	594	3.78				
Powder Mill to Lake William	226	0.98	377	1.82	610	0.83
Powder Mill L. (sediment)	272	38.00				
Three Mile Lake to Powder Mill	n.s.		319	2.25	288	3.30
Three Mile L. (sediment)	34	0.44				

n.s. = not sampled.

the sediment during anoxic conditions in the lakes and precipitated or were adsorbed on suspended solids in the lakes.

The calculated quantities of As and Hg transported by water and suspended solids by the connecting creeks are shown in Table 7. The calculation is based on a monthly discharge reported by the Water Resources Branch (1984). The transported quantities of As and Hg estimated for April are based only on a single discharge reading.

The transported quantity of As by water is expressed as the difference in As concentration in each creek and that in the receiving lake. These concentrations are summarized in Figure 3. For example the net transport of As from Muddy Pond into Lake Thomas in June 1983 was assumed to be the difference between 0.047 $mg.L^{-1}$ of As concentration in Muddy Pond outlet and 0.0040 $mg.L^{-1}$ of As concentration in Lake Thomas water. The concentration of As in creek water and receiving lakes was often similar, for example in the creek connecting Lake William with Lake Thomas in April. However, the concentration of As was higher in some lakes than in the inflowing creeks, for example the concentration of As was higher in Lake Thomas water than in the inflowing creek from Lake William in June and August. This increase indicated another source of As in addition to the inflowing creek, such as bottom sediments or suspended solids which may release As under different conditions in the lake, or leachates from As-containing material in the lake drainage basin such as mine wastes or arsenopyrite in the rocks.

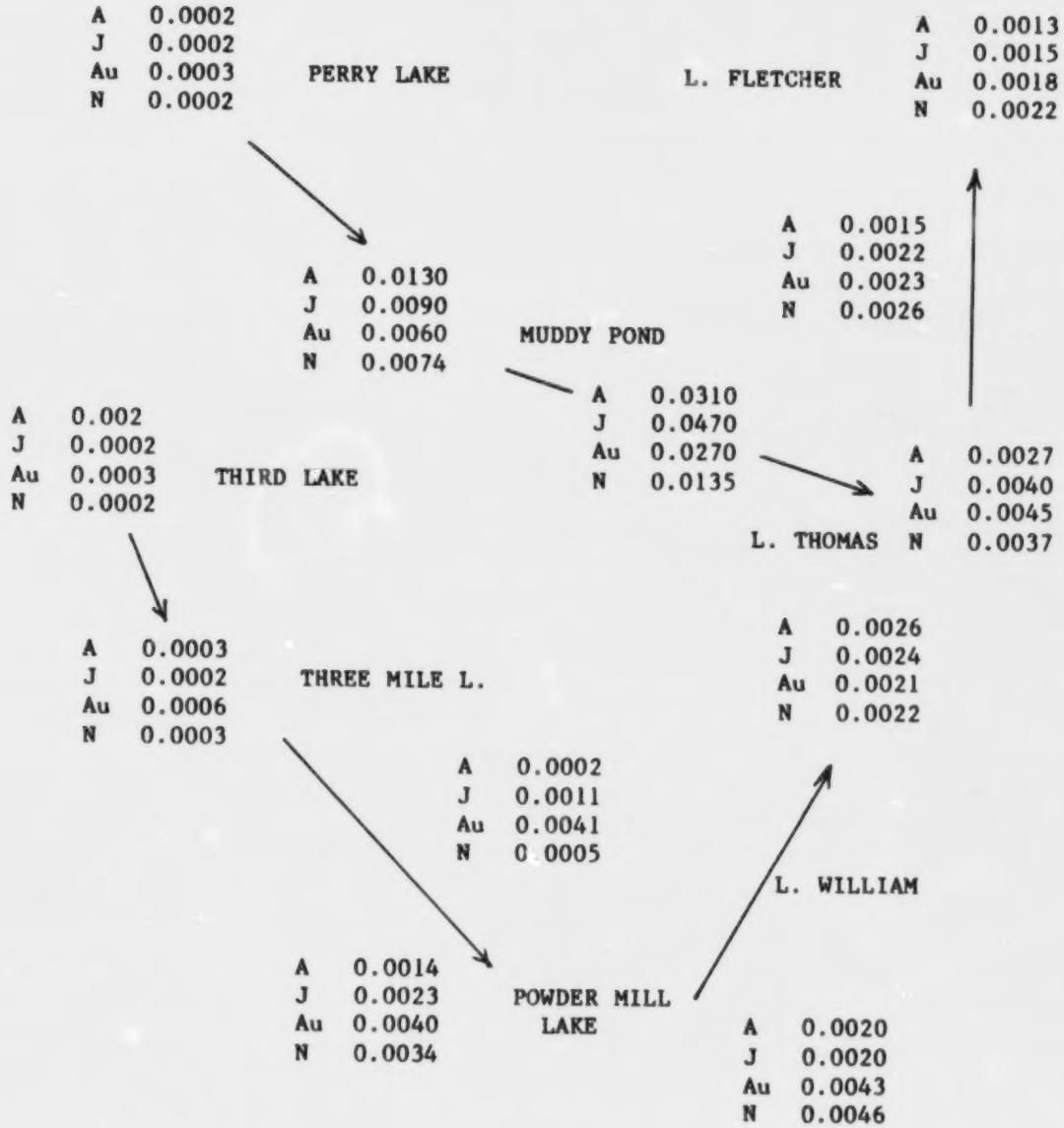
Table 7. Calculated quantities of As and Hg transported by the connecting streams in suspended solids and water (per month)

Creek	Month	As (by suspended solids)	As (by water)	Hg (by suspended solids)
Powder Mill L. to Williams	April	0.95 kg	n.s.	4.00 g
	June	n.s.	n.s.	n.s.
	August	0.08 kg	n.s.	0.36 g
	November	1.82 kg	n.s.	2.47 g
L. Williams to L. Thomas	April	2.86 kg	Nil	7.70 g
	June	n.s.	Nil	n.s.
	August	0.24 kg	Nil	0.90 g
	November	7.10 kg	Nil	5.03 g
L. Thomas to L. Fletcher	April	3.70 kg	2.96 kg	11.00 g
	June	n.s.	4.66 kg	n.s.
	August	0.90 kg	2.23 kg	2.00 g
	November	7.10 kg	6.29 kg	13.66 g
Muddy Pond to L. Thomas	April	0.26 kg	5.32 kg	1.33 g
	June	n.s.	3.12 kg	n.s.
	August	0.03 kg	0.42 kg	0.45 g
	November	0.81 kg	2.28 kg	2.75 g

n.s. = not sampled.

Nil = no net transport.

CONCENTRATION OF As IN LAKE AND STREAM WATER, 1983



Concentrations in $mg.L^{-1}$

A = April
J = June
Au = August
N = November

The greatest quantity of As was transported by water from Muddy Pond into Lake Thomas (Table 5). The concentration of As in Muddy Pond water was lower than that in the outflowing creek during all sampling periods. Water samples in the Muddy Pond were collected at the deepest point. The data indicate input of As into the water in the area between the deepest point and Muddy Pond outlet. The most possible source is the bottom sediment, which contains almost 1% of As in some areas in the Muddy Pond. The greatest quantity of As in suspended solids was transported from Lake Thomas into Lake Fletcher in November (7.1 kg per month) and in April (3.7 kg per month). The transport of As by water was highest from Muddy Pond into Lake Thomas in April (5.3 kg per month).

The greatest quantity of Hg in suspended solids was transported from Lake Thomas into Lake Fletcher in April (11.0 g per month) and from Lake Williams into Lake Thomas during the same month (7.7 g per month). Because the concentration of Hg was below the detection limit, the transport of Hg by creek water could not be calculated.

The changes in the mean monthly creek discharges affected the quantities of transported As and Hg. Although there was a relative increase in concentration of As and Hg in suspended solids in most of the creeks, the transported amounts were smallest during the low discharge in August (Table 7). The discharge of the creek connecting Muddy Pond with Lake Thomas was the smallest of all measured streams. However, signficant quantities of particulate As

and Hg were transported by this creek into Lake Thomas. In addition, concentrations of As, Hg, Pb and Zn in suspended solids in this creek were the highest from all five creeks sampled, particularly in August (Table 2). The results indicate solubilization of metals from Muddy Pond sediment during summer anoxic conditions. Solubilized metals adsorbed on the suspended particles are further transported by the stream into Lake Thomas.

ACKNOWLEDGEMENTS

Water Resources Branch, Environment Canada set up gauges at the outflow streams and calcualted the water discharge values used in loading calculations.

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FISH CONTAMINATION IN THE UPPER SHUBENACADIE BASIN STUDY AREA

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INTRODUCTION

In freshwater systems, fish are usually at the top of what can be called the food chain. Because of this position, they are usually the segment of the biota which has the greatest potential for accumulating contaminants which are passed to them by their food items. Interpreting fish contaminant data, however, can be very difficult at times due to their complex life histories, their feeding habits and preferences and their after high mobility.

Previous reports in this document have demonstrated the presence of elevated concentrations of arsenic in water, sediments and suspended sediment of most of the study lakes, mercury in sediments and suspended solids in a number of the lakes and lead in sediments of Powder Mill Lake. As fish are known to be in all the study lakes, and they are known to accumulate contaminants and as some species are often consumed by local fishermen, it was decided to see if there was any transport of contaminants from water and sediments to fish and to see if any patterns could be detected in the distribution of arsenic, mercury and other metals.

The purpose of this work was then to sample the study lakes to see what species could be found, to analyze tissue samples for contaminant concentrations and, if justified, make recommendations for further, more detailed work.

METHODS

Collection of fish samples was done by the Department of Fisheries and Oceans using a gill net set overnight. Nets were set in Muddy Pond, Powder Mill Lake, Lake William and Lake Thomas. Collected fish were measured and weighed, cleaned and forwarded frozen to the Water Quality Branch laboratory in Moncton. Filet samples were analyzed for lead, cadmium, mercury and arsenic according to the Water Quality Branch Analytical Methods Manual (1979), where samples were acid digested and the extract was analyzed by atomic absorption.

RESULTS AND DISCUSSION

The analytical results from this study are displayed in Table 1. It is evident that in the case of lead and cadmium the levels are below detection except in one White Perch (Morone americanas) from Lake Thomas where lead is detected at 0.08 $mg.kg^{-1}$. In polluted waters Cd can reach levels in fish muscle of 0.13 $mg.kg^{-1}$, and is usually much higher in liver tissue where it is concentrated (Reeder et al, 1979). Lead in polluted water has been measured in fish muscle at an average of 1.78 $mg.kg^{-1}$, but in uncontaminated water levels average anywhere from 0.04 to 0.19. In Shubenacadie basin fish, the levels of Pb and Cd appear to be as low or lower than average levels in uncontaminated waters elsewhere. Pb and Cd can be assumed, for the purpose of this discussion, to be sufficiently low as to be unimportant.

Table 1. Summary of fish locations, sizes and contaminant levels

Location	Fish	Length (mm)	Weight (g)	Pb $mg.kg^{-1}$	Hg $mg.kg^{-1}$	Cd $mg.kg^{-1}$	As $mg.kg^{-1}$
Powder Mill L.	White Perch	260	292.9	<0.05	1.98	<0.025	0.013
	White Perch	300	454.2	<0.05	2.00	<0.025	0.009
	White Perch	200	124.5	<0.05	0.76	<0.025	0.022
	White Sucker	293	312.2	<0.05	0.11	<0.025	0.028
	White Sucker	250	184 2	<0.05	0.21	<0.025	0.062
	White Sucker	252	217.1	<0.05	0.18	<0.025	0.062
	Black Bass	161	61.3	<0.05	0.575	<0.025	0.030
Lake William	White Perch	181	108.9	<0.05	0.985	<0.025	0.023
	White Perch	191	114.7	<0.05	0.70	<0.025	0.023
	White Perch	180	112.3	<0.05	0.69	<0.025	0.018
	White Perch	182	106.5	<0.05	0.72	<0.025	0.012
	Black Bass	189	84.2	<0.05	0.675	<0.025	0.025
Lake Thomas	White Sucker	360	526.6	<0.05	0.50	<0.025	0.012
	White Sucker	400	700.0	<0.05	0.68	<0.025	0.031
	White Sucker	370	588.9	<0.05	0.485	<0.025	0.019
	White Perch	145	48.0	<0.05	0.28	<0.025	0.030
	White Perch	200	135.2	<0.05	1.88	<0.025	0.011
	White Perch	155	59.8	<0.05	0.425	<0.025	0.261
	White Perch	190	110.2	<0.05	0.955	<0.025	0.018
	White Perch	160	66.4	<0.05	0.675	<0.025	0.037
	White Bass	230	159.7	<0.05	0.95	<0.025	0.031
Muddy Pond	Brook Trout			<0.05	0.215	<0.025	0.041
	Brook Trout			<0.05	0.385	<0.025	0.024
	Brook Trout			<0.05	0.32	<0.025	0.022
	Brook Trout			<0.05	0.395	<0.025	0.032
	Brook Trout			<0.05	0.42	<0.025	0.026
	White Sucker			<0.05	0.395	<0.025	0.151

Arsenic

The results for arsenic are summarized in Table 2. Levels ranged between 0.009 and 0.261 $mg.kg^{-1}$ (wet weight) with an overall average of 0.040 $mg.kg^{-1}$ (all fish). The average for White Perch was 0.037 $mg.kg^{-1}$ (0.009-0.261), while the average for White Suckers (Catastomus commersoni) was 0.052 $mg.kg^{-1}$ As (0.012-0.151). These levels approach the upper end of the average level in freshwater fish (edible parts) in Canada which varies from 0.01 to 0.62 $mg.kg^{-1}$ (Demayo et al, 1979).

Arsenic levels in fish appear to be elevated in Powder Mill Lake and Lake Thomas compared with Lake William. Unfortunately, no White Perch were collected from Muddy Pond but the one White Sucker from that lake is also high (0.151 $mg.kg^{-1}$). Arsenic levels in Brook Trout (Salvilinus fontinalis) from Muddy Pond are comparable with other fish from Lake Thomas and Powder Mill Lake.

The occurrence of arsenic in fish found in waters close to gold mining areas has been documented. Falk et al (1973) reported levels as high as 1.69 and 0.29 $mg.kg^{-1}$ in muscle of Pike and Walleye respectively from Grace Lake, NWT. Much of the arsenic in Canadian waters comes from natural sources through leaching and runoff from arsenic-rich soil and rock. Gold mining areas are naturally rich in arsenic and the process of mining and the exposure of arsenic-rich rock in the mines and tailings facilitates the normal geological processes resulting in high levels of arsenic in surrounding lakes and

Table 2. Summary of arsenic concentrations in fish muscle

Location	Species (N)	Mean $mg.kg^{-1}$	range
Powder Mill L.	White Perch (3)	0.015	0.009-0.02
	White Sucker (3)	0.051	0.028-0.06
	Black Bass (1)	0.030	-
Lake William	White Perch (4)	0.019	0.012-0.02
	Black Bass (1)	0.025	-
Lake Thomas	White Perch (5)	0.071	0.011-0.26
	White Sucker (3)	0.023	0.012-0.03
	Black Bass (1)	0.031	-
Muddy Pond	Brook Trout (5)	0.029	0.022-0.04
	White Sucker (1)	0.151	-

groundwater. Arsenic in the water and sediment is accumulated by the biota but does not appear to be magnified through the food chain. Concentrations of arsenic in fish have been positively correlated with concentrations in the water, but no correlation has been found between the fish length, weight or condition (Sorensen, 1976).

Mercury

The level of mercury above which fish are considered unsuitable for human consumption is 0.5 $mg.kg^{-1}$ (wet weight). Many of the fish collected from the four lakes studied here exceeded this level (Table 3) and could be considered "contaminated". The overall average for all the fish sampled was 0.68 $mg.kg^{-1}$ Hg (range 0.11 to 2.00 $mg.kg^{-1}$).

Only one of the White Suckers exceeded the 0.5 $mg.kg^{-1}$ level, but all except two of the White Perch were higher as were all the Black Bass (Micropterus dolomieui). None of the trout exceeded 0.5 $mg.kg^{-1}$.

Mercury concentrations in fish from Powder Mill Lake and Lake Thomas are higher than Lake William and Muddy Pond. The highest levels in White Perch occur in Powder Mill (2.00 and 1.98 $mg.kg^{-1}$), whereas the highest levels in White Suckers occurred in fish from Lake Thomas (0.68 $mg.kg^{-1}$). The one sucker collected from Muddy Pond had a Hg concentration (0.40 $mg.kg^{-1}$) close to the total average for suckers (i.e. 0.36). Unfortunately, no White Perch were collected from Muddy Pond.

When mercury levels for the White Suckers collected in these lakes are compared with average concentrations in other parts of Canada (Sherbin, 1979), it is evident that the White Sucker in this system has elevated mercury concentrations. Mean mercury values for White Suckers from 36 relatively uncontaminated sites in Labrador were

Table 3. Summary of mercury in fish muscle

Location	Species (N)	Mean $mg.kg^{-1}$	range
Powder Mill L.	White Perch (3)	1.58	0.76 -2.00
	White Sucker (3)	0.17	0.11 -0.21
	Black Bass (1)	0.575	-
Lake William	White Perch (4)	0.77	0.69 -0.98
	Black Bass (1)	0.67	-
Lake Thomas	White Perch (5)	0.84	0.425-1.88
	White Sucker (3)	0.56	0.50 -0.68
	Black Bass (1)	0.95	-
Muddy Pond	Brook Trout (5)	0.35	0.215-0.42
	White Sucker (1)	0.39	-

0.16 $mg.kg^{-1}$, whereas fifty-four fish from six areas in the Smallwood Reservoir, Labrador, an area suspected of high natural Hg levels, had a mean value of 0.35 $mg.kg^{-1}$ (Bruce & Spencer, 1979). White Suckers in Lake Thomas (0.56 $mg.kg^{-1}$) and Muddy Pond (0.39 $mg.kg^{-1}$) both exceed the average in Smallwood Reservoir.

White Perch display an even higher level of mercury contamination in the study lakes. The average mercury level of samples collected in Ontario range between 0.15 and 0.19 $mg.kg^{-1}$ (Sherbin, 1979), whereas the average in the study lakes is 1.0 $mg.kg^{-1}$.

Mercury, unlike arsenic, magnifies in the aquatic biota. Very low non-toxic levels of mercury in the water can result in higher levels as one proceeds up the food chain. Obviously sufficient mercury is available in the study lakes to influence levels in White Suckers and particularly in the White perch. In fact, many of the fish in this system have sufficient levels of mercury to suffer some of the sub-lethal effects observed at levels as low as 0.23 $mg.kg^{-1}$ methyl mercury in muscle (Lindahl & Schwanbon, 1971a,b). These effects include decrease in muscle fitness which reduces swimming ability, and also central nervous system defects.

CONCLUSIONS

Fish in Muddy Pond, Lake Thomas and Powder Mill Lake have elevated levels of mercury in muscle tissue. These lakes surround a centre of gold mining and ore crushing which was carried out during the early 1900's. It is evident that mercury released to the environment at that time remains in the system in sufficient quantities to be accumulated by the biota and to be transferred to fish through feeding or possibly from the water. Levels here compare with levels at contaminated sites elsewhere in Canada.

Arsenic levels in Powder Mill Lake and Lake Thomas are elevated, indicating a source of arsenic in the sediment or water of this system. Since arsenic-rich rock and groundwater are known to be common in the area these findings are not surprising.

Both arsenic and mercury are relatively low in fish from Lake William. This lake receives the outflow from Powder Mill near its own outlet to Lake Thomas. This fact and the size of Lake William as well as its location on the periphery of the mining area probably account for the lower values.

Human health is probably not threatened by levels of Hg and As in fish from the study lakes. White Perch and White Suckers are not popular sport fish and are unlikely to be consumed. Brook Trout do not seem to have accumulated mercury or arsenic to any serious extent. Hg levels in trout were all below 0.5 $mg.kg^{-1}$. Black Bass are a popular sport fish and in all three cases measured, exceeded the 0.5 $mg.kg^{-1}$ "safe" level. A further sampling for Black Bass and determination of its use as a sport fish in these lakes should be carried out to better assess the threat to human health from Hg in this species.

This study has established that contamination of fish in the upper Shubenacadie Basin is a problem. Further work can now be contemplated which will identify the sources of contamination to fish, (i.e. food types, habitat preference, etc.) and examine the effects on growth and other potential effects these contaminants can have on both the fish and human lake basin population.

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APPENDIX I

APRIL 1983

1. **Water Sampling:**

in Lakes Three Mile, Powder Mill, Thomas, Third, Fletcher, Perry and Muddy Pond; at the deepest point in each lake, 1 m from the surface, 2 m off the bottom and in the middle of the water columns.

Parameters determined:

pH, alkalinity, temperature profile, dissolved oxygen profile, Secchi disk, colour, organic C, conductivity

major ions (Ca, Mg, K, Na, Si, SO_4^{-2}, Cl^{-1})

nutrients (TN, NO_3-N, NH_4-N, TP, SRP)

metals (Pb, Zn, Cu, Cr, Co, Cd, Ni, Fe, Mn, Hg, As)

Agency responsible for sampling:

Nova Scotia Department of Environment

Agency responsible for analyses:

IWD, Water Quality Branch, Moncton, N.B.

2. **Suspended Solids and Water Sampling in the Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mile Lake - Powder Mill Lake.

2.1 Suspended solids sampling: about 5,000 L of water from each stream to be processed through the Westphalia separator; about

30 L of water processed through a Sartorius filtering system to quantify the suspended solids at each site during the sampling period.

Parameters determined:

Hg, As, organic and inorganic C, N

(if sufficient quantity of material is obtained - Pb, Cu, Zn, Ni, Cr, Co, Cd, and possibly Si, Ca, K, Na, Mg, P, Fe, Mn)

Agency responsible for sampling:

National Water Research Institute, Burlington, Ontario

Agency responsible for analyses:

National Water Research Institute, Burlington, Ontario

2.2 Water sampling: at the sites identical with those for suspended solids.

Parameters determined:

identical with those selected for water samples collected in the lakes (under 1).

Agency responsible for sampling:

Nova Scotia Department of Environment

Agency responsible for analyses:

IWD, Water Quality Branch, Moncton, N.B.

3. **Monitoring Discharge of the Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mile Lake - Powder Mill Lake.

Agency responsible for monitoring:

IWD, Water Resources Branch and EPS, Atlantic Region.

MAY 1983

1. **Monitoring Discharge of the Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mile Lake - Powder Mill Lake.

Agency responsible for the monitoring:

Water Resource Branch and EPS, Atlantic Region

JUNE 1983

1. **Water Sampling:**

in Lakes Three Mile, Powder Mill, Thomas, Third, Fletcher, Perry and Muddy Pond; at the deepest point in each Lake; under isothermal conditions at the sampling site 1 m from the surface, 2 m off the bottom, middle of the water column. In the lakes which will be stratified at this time of sampling, 1 m from the surface, at a second depth in the epilimnion, at the thermocline, 2 m off the bottom and at a second depth in the hypolimnion.

Parameters determined:

pH, alkalinity, temperature profile, dissolved oxygen profile, Secchi dish, colour, organic C, conductivity

major ions (Ca, Mg, K, Na, Si, SO_4^{-2}, Cl^{-1})

nutrients (TN, NO_3-N, NH_4-N, TP, SRP)

metals (Pb, Zn, Cu, Cr, Co, Cd, Ni, Fe, Mn, Hg, As)

Agency responsible for sampling:

Nova Scotia Department of Environment

Agency responsible for analyses:

IWD, Water Quality Branch, Moncton, N.B.

2. **Water Sampling in Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mill Lake - Powder Mill Lake. Samples will be collected at the same sites

Parameters determined:

identical with those selected for water samples from the lakes.

Agency responsible for sampling:

Nova Scotia Department of Environment

Agency responsible for analyses:

IWD, Water Quality Branch, Moncton, N.B.

3. **Monitoring Discharge of the Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mile Lake - Powder Mill Lake.

Agency responsible for monitoring:

IWD, Water Resources Branch and EPS, Atlantic Region.

JULY 1983

1. Monitoring Discharge of the Connecting Streams:

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mile Lake - Powder Mill Lake.

Agency responsible for the monitoring:

IWD, Water Resources Branch and EPS, Atlantic Region.

AUGUST 1983

1. **Water Sampling:**

in Lakes Three Mile, Powder Mill, Thomas, Third, Fletcher, Perry and Muddy Pond; at the deepest point in each Lake; under isothermal conditions at the sampling site 1 m from the surface, 2 m off the bottom, middle of the water column. In the lakes which will be stratified at this time of sampling, 1 m from the surface, at a second depth in the epilimnion, at the thermocline, 2 m off the bottom and at a second depth in the hypolimnion.

Parameters determined:

pH, alkalinity, temperature profile, dissolved oxygen profile, Secchi dish, colour, organic C, conductivity

major ions (Ca, Mg, K, Na, Si, SO_4^{-2}, Cl^{-1})

nutrients (TN, NO_3-N, NH_4-N, TP, SRP)

metals (Pb, Zn, Cu, Cr, Co, Cd, Ni, Fe, Mn, Hg, As)

Agency responsible for sampling:

Nova Scotia Department of Environment

Agency responsible for analyses:

IWD, Water Quality Branch, Moncton, N.B.

2. **Suspended Solids and Water Sampling in Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mile Lake - Powder Mill Lake.

2.1 Suspended solids sampling: about 5,000 L of water from each stream to be processed through the Westphalia separator; about 30 L of water processed through a Sartorius filtering system to quantify the suspended solids at each site during the sampling period.

Parameters determined:

Hg, As, organic and inorganic C, N

(if sufficient quantity of material is obtained - Pb, Cu, Zn, Ni, Cr, Co, Cd, and possibly Si, Ca, K, Na, Mg, P, Fe, Mn)

Agency responsible for sampling:

National Water Research Institute, Burlington, Ontario

Agency responsible for analyses:

National Water Research Institute, Burlington, Ontario

2.2 Water sampling: at the sites identical with those for suspended solids.

Parameters determined:

identical with those selected for water samples collected in the lakes (under 1).

Agency responsible for sampling:

Nova Scotia Department of Environment

Agency responsible for analyses:

IWD, Water Quality Branch, Moncton, N.B.

3. **Monitoring Discharge of the Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mile Lake - Powder Mill Lake.

Agency responsible for monitoring:

IWD, Water Resources Branch and EPS, Atlantic Region.

4. **Sediment Sampling:**

4.1 Coring - at the deepest point in Lakes Powder Mill, Thomas and other selected five lakes. Few sediment cores will be obtained from Muddy Pond. All sediment cores will be subdivided into 1 cm sections. Part of each wet subsample will be stored for further determination of organic contaminants. One sediment core from each lake will be stored for dating by Pb-210 and Cs-137.

Parameters determined:

Inorganics:

Major elements (Si, Al, Fe, Mg, Ca, K, Na, Mn, P, inorganic and organic carbon)

Metals (Pb, Cu, Cr, Co, Cd, Ni, Zn, Hg, As)

Organics:

phthalate esters (di-octyl phthalate) or the phthalic acid derivatives of these compounds

chlorophenols

chlorobenzenes

PCB

PAH (selected)

ETU (ethyl-thio-urea, a derivative of thiocarbamate pesticides)

chlordane

toxaphene

Agency responsible for sampling:

National Water Research Institute, Burlington, Ontario

Agency responsible for analyses (Inorganics):

National Water Research Institute, Burlington, Ontario

Organics: samples frozen and stored for later analyses.

4.2 Surface sediment and water samples from Perry Lake.

Parameters determined:

Sediment:

same as under 4.1. Inorganics.

Water:

same as for the other lakes sampled under 1.

Agency responsible for sampling:

Nova Scotia Department of Environment and National Water Research Institute, Burlington, Ontario

Agency responsible for analyses:

IWD, Water Quality Branch, Mondon, N.B. and National Water Research Institute, Burlington, Ontario

4.3 Cores from the beach located at the NW-corner of Powder Mill Lake will be collected and subsampled into 2 cm sections.

Surface sediment from the deepest point in Loon Lake.

Parameters determined:

As, Hg, inorganic and organic C.

Agency responsible for sampling:

National Water Research Institute, Burlington, Ontario

Agency responsible for analyses:

National Water Research Institute, Burlington, Ontario

SEPTEMBER 1983

1. **Monitoring Discharge of the Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mile Lake - Powder Mill Lake.

Agency responsible for monitoring:

IWD, Water Resources Branch and EPS, Atlantic Region.

OCTOBER 1983

1. **Water Sampling:**

in Lakes Three Mile, Powder Mill, Thomas, Third, Fletcher, Perry and Muddy Pond; at the deepest point in each Lake; under isothermal conditions at the sampling site 1 m from the surface, 2 m off the bottom, middle of the water column. In the lakes which will be stratified at this time of sampling, 1 m from the surface, at a second depth in the epilimnion, at the thermocline, 2 m off the bottom and at a second depth in the hypolimnion.

Parameters determined:

pH, alkalinity, temperature profile, dissolved oxygen profile, Secchi disk, colour, organic C, conductivity

major ions (Ca, Mg, K, Na, Si, SO_4^{-2}, Cl^{-1})

nutrients (TN, NO_3-N, NH_4-N, TP, SRP)

metals (Pb, Zn, Cu, Cr, Co, Cd, Ni, Fe, Mn, Hg, As)

Agency responsible for sampling:

Nova Scotia Department of Environment

Agency responsible for analyses:

IWD, Water Quality Branch, Moncton, N.B.

2. **Water Sampling in Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mill Lake - Powder Mill Lake. Samples will be collected at the same sites as in April 1983.

Parameters determined:

Identical with those selected for water samples from the lakes.

Agency responsible for sampling:

Nova Scotia Department of Environment

Agency responsible for analyses:

IWD, Water Quality Branch, Moncton, N.B.

3. **Monitoring Discharge of the Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mile Lake - Powder Mill Lake.

Agency responsible for monitoring:

IWD, Water Resources Branch and EPS, Atlantic Region.

NOVEMBER 1983

1. **Monitoring Discharge of the Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mile Lake - Powder Mill Lake.

Agency responsible for the monitoring:

IWD, Water Resources Branch and EPS, Atlantic Region.

2. **Suspended Solids and Water Sampling in Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mile Lake - Powder Mill Lake.

2.1 Suspended solids sampling: about 5,000 L of water from each stream to be processed through the Westphalia separator; about 30 L of water processed through a Sartorius filtering system to quantify the suspended solids at each site during the sampling period.

Parameters determined:

Hg, As, organic and inorganic C, N

(if sufficient quantity of material is obtained - Pb, Cu, Zn, Ni, Cr, Co, Cd, and possibly Si, Ca, K, Na, Mg, P, Fe, Mn)

Agency responsible for sampling:

National Water Research Institute, Burlington, Ontario

Agency responsible for analyses:

National Water Research Institute, Burlington, Ontario

2.2 Water sampling: at the sites identical with those for suspended solids.

Parameters determined:

identical with those selected for water samples collected in the lakes (April 1983, under 1).

Agency responsible for sampling:

Nova Scotia Department of Environment

Agency responsible for analyses:

IWD, Water Quality Branch, Moncton, N.B.

DECEMBER 1983

1. **Water Sampling:**

in Lakes Three Mile, Powder Mill, Thomas, Third, Fletcher, Perry and Muddy Pond; at the deepest point in each Lake; 1 m from the surface, 2 m off the bottom and in the middle of the water column.

Parameters determined:

pH, alkalinity, temperature profile, dissolved oxygen profile, Secchi disk, colour, organic C, conductivity

major ions (Ca, Mg, K, Na, Si, SO_4^{-2}, Cl^{-1})

nutrients (TN, NO_3-N, NH_4-N, TP, SRP)

metals (Pb, Zn, Cu, Cr, Co, Cd, Ni, Fe, Mn, Hg, As)

Agency responsible for sampling:

Nova Scotia Department of Environment

Agency responsible for analyses:

IWD, Water Quality Branch, Moncton, N.B.

2. **Water Sampling in Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mill Lake - Powder Mill Lake. Samples will be collected at the same sites as in April 1983.

Parameters determined:

Identical with those selected for water samples from the lakes.

Agency responsible for sampling:

Nova Scotia Department of Environment

Agency responsible for analyses:

IWD, Water Quality Branch, Moncton, N.B.

3. **Monitoring Discharge of the Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mile Lake - Powder Mill Lake.

Agency responsible for monitoring:

IWD, Water Resources Branch and EPS, Atlantic Region.

JANUARY 1984

1. **Monitoring Discharge of the Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mile Lake - Powder Mill Lake.

Agency responsible for the monitoring:

IWD, Water Resources Branch and EPS, Atlantic Region

FEBRUARY 1984

1. **Monitoring Discharge of the Connecting Streams:**

Muddy Pond - Lake Thomas; Lake William - Lake Thomas; Powder Mill Lake - Lake William; Lake Thomas - Fletcher Lake; Three Mile Lake - Powder Mill Lake.

Agency responsible for the monitoring:

IWD, Water Resources Branch and EPS, Atlantic Region

APPENDIX II

MERCURY AMALGAMATION

The most common method of gold extraction in Waverley and Montague was the mercury amalgamation process. This process is based on the affinity of elemental mercury for gold in the free metallic state. In chemical terms, an amalgam is an alloy of mercury.

Mile "run" ore was crushed in a stamp mill and mixed with water after the larger pieces of non-gold bearing rock were removed. As a "rule of thumb", the same amount of mercury as of gold believed to be in the ore was used in the process. The amalgam was removed and the remaining pulp washed over mercury coated copper plates for further extraction. The tailings were discarded and the amalgam retorted to effect separation of the mercury from the gold.

Up to 25% of the mercury added in the amalgamation process was not recovered. Mercury was lost to the atmosphere in retorting, surrounding the environment via tailings disposal, and within the mill itself through mishandling.

As mentioned earlier, there was 73,105 and 68,139 ounces of gold extracted from the Waverley and Montague areas, respectively. Using this data and the general "rule of thumb" approach (i.e., a 1:1 ratio of mercury and gold in the amalgamation process), then approximately 5,000 and 4,500 pounds of mercury was used by Waverley and Montague, respectively, over the course of mining at each gold district. Using the estimate that approximately 25% of this was lost to the environment, then 1,200 pounds of mercury was lost in the Waverley area, and 1,100 pounds of mercury was lost in the Montague area.

CYANIDATION

The mercury amalgamation process could not directly extract gold bound in sulphide ores. In the early 1900s the cyanide process came into use to refine these contaminated ores.

Only a small amount of cyanide is required for this process (approximately 1- 4 pounds of potassium cyanide per ton of ore). Gold is dissolved from the solid state by this weak cyanide solution. The gold then forms a weak complex with the cyanide. This gold-bearing solution is termed pregnant and is referred to as "pregs" by the miners.

The pregnant solution is separated from the insoluble residue of ore, probably by filtration. The precipitation of gold from this solution is effected by adding zinc dust, in excess of the gold in the solution; zinc forms a stronger cyanide complex than gold. The gold is released from the cyanide complex and forms a precipitate in the solution. Although the exact nature of the chemical reaction is not agreed upon by chemists, one proposed mechanism is as follows:

$$K\,Au\,(CN)_2 + 2\,KCN + Zn + H_2O = K_2Zn\,(CN)_4 + Au + H + KOH$$

Once the gold is precipitated out of solution, the solution is termed "barren". The gold is then easily separated out (probably by filtration) and the barren solution is allowed to run into the district drainage area.

A pulp containing metallic gold in course particles would require so long a cyanide treatment to dissolve the gold into solution that it would render the process uneconomical. In such cases, preliminary removal of the metal would be accomplished by amalgamation.

APPENDIX III

VALUES FOR pH, DISSOLVED OXYGEN AND EXTRACTABLE METALS IN THE STUDY LAKES

THIRD LAKE

	Depth	DO ($mg.L^{-1}$)	pH	Pb[1] ($mg.L^{-1}$)	As[2] ($mg.L^{-1}$)	Mn[3] ($mg.L^{-1}$)	Al[4] ($mg.L^{-1}$)	Fe ($mg.L^{-1}$)	Ni[5] ($mg.L^{-1}$)
23 April	1	12.0	6.5	L	L	L	CON[6]	0.02	CON
	8	12.0	6.6	0.002	L	L	CON	0.02	CON
	21	12.0	6.6	L	0.0002	L	CON	0.02	CON
13 June	1	9.4	6.1	L	0.0002	0.01	0.015	0.02	L
	12	9.2	6.1	L	L	L	0.015	0.01	L
	21	8.4	6.1	L	L	L	0.02	0.02	L
18 Aug.	1	9.2	6.3	0.002	0.0002	0.01	L	0.01	0.002
	5	9.0	6.4	L	0.0002	0.01	L	0.01	L
	9	8.9	4.4	L	0.0002	0.01	0.01	0.01	L
	15	6.3	6.1	0.003	0.0003	0.06	0.02	0.07	L
	21	5.0	6.1	0.003	0.0003	0.11	0.02	0.12	L
1 Dec.	1	11.8	6.5	L	0.0002	0.02	0.03	0.04	L
	10	11.8	6.4	L	0.0002	0.02	0.015	0.037	L
	21	11.8	6.5	L	0.0002	0.02	0.02	0.04	L

[1] - Less than detection level of 0.002 $mg.L^{-1}$
[2] - Less than detection level of 0.0002 $mg.L^{-1}$
[3] - Less than detection level of 0.01 $mg.L^{-1}$
[4] - Less than detection level of 0.01 $mg.L^{-1}$
[5] - Less than detection level of 0.001 $mg.L^{-1}$
[6] - Contaminated.

THREE MILE LAKE

	Depth	DO ($mg.L^{-1}$)	pH	Pb[1] ($mg.L^{-1}$)	As ($mg.L^{-1}$)	Mn ($mg.L^{-1}$)	Al[2] ($mg.L^{-1}$)	Fe ($mg.L^{-1}$)	Ni[3] ($mg.L^{-1}$)
27 April	1	11.4	6.5	L	0.0002	0.01	CON[6]	0.04	CON
	4	12.0	6.5	L	0.0002	0.01	CON	0.04	CON
	9	12.1	6.4	L	0.0004	0.02	CON	0.05	CON
14 June	1.0	9.0	6.3	L	0.0002	0.03	0.025	0.05	L
	4	9.3	6.4	L	0.0002	0.03	0.01	0.05	L
	6	8.9	6.4	L	0.0002	0.03	0.01	0.05	L
22 Aug.	1	9.0	6.4	L	0.0007	0.07	0.01	0.08	L
	4	8.6	6.3	L	0.0007	0.07	L	0.07	0.001
	6	5.8	6.2	L	0.0005	0.22	0.01	0.05	L
	7	4.5	6.2	0.002	0.0005	0.5	0.01	0.04	0.001
23 Nov.	1	9.0	6.5	L	0.0002	0.03	0.025	0.12	L
	5	9.0	6.6	L	0.0004	0.03	0.025	0.12	L
	10	9.0	6.5	0.002	0.0004	0.03	0.03	0.12	L

[1] - Less than detection level of 0.002 $mg.L^{-1}$
[2] - Less than detection level of 0.01 $mg.L^{-1}$
[3] - Less than detection level of 0.001 $mg.L^{-1}$
[4] - Contaminated

THREE MILE LAKE TO POWDER MILL LAKE

	pH	Pb[1] ($mg.L^{-1}$)	As ($mg.L^{-1}$)	Mn ($mg.L^{-1}$)	Al ($mg.L^{-1}$)	Fe ($mg.L^{-1}$)	Ni[2] ($mg.L^{-1}$)
05 May	6.6	L	0.0002	0.03	CON[3]	0.05	L
15 June	6.5	L	0.0011	0.09	0.015	0.11	L
22 Aug.	6.3	L	0.004	0.13	0.01	0.28	L
23 Nov.	6.4	L	0.0005	0.03	0.035	0.12	L
16 Feb.	6.3	L	0.0004	0.07	0.04	0.09	CON

[1] - Less than detection level of 0.002 $mg.L^{-1}$
[2] - Less than detection level of 0.001 $mg.L^{-1}$
[3] - Contaminated

POWDER MILL LAKE

	Depth	DO ($mg.L^{-1}$)	pH	Pb[1] ($mg.L^{-1}$)	As ($mg.L^{-1}$)	Mn ($mg.L^{-1}$)	Al[2] ($mg.L^{-1}$)	Fe ($mg.L^{-1}$)	Ni[3] ($mg.L^{-1}$)
26 April	1	11.3	6.8	L	0.0011	0.01	CON[3]	0.06	CON
	4	11.0	6.7	L	0.0016	0.01	CON	0.05	CON
	7	11.0	6.9	L	0.0014	0.01	CON	0.05	CON
14 June	1	9.0	6.7	L	0.0024	0.02	0.015	0.06	L
	7	9.0	6.7	L	0.0022	0.02	0.015	0.04	L
	12	5.5	6.5	L	0.0024	1.1	0.063	0.07	L
18 Aug.	1	8.8	6.6	L	0.0045	0.02	0.02	0.03	L
	3	8.8	6.5	L	0.0043	0.02	0.01	0.04	L
	7	6.4	6.3	L	0.0025	0.04	0.01	0.03	L
	9	4.0	6.3	L	0.0045	0.94	0.01	0.54	0.003
1 Dec.	1	12.5	6.8	L	0.003	0.03	0.035	0.09	L
	7	12.3	6.8	L	0.003	0.03	0.027	0.1	L
	13	12.3	6.7	0.002	0.004	0.03	0.06	0.15	L

[1] - Less than detection level of 0.002 $mg.L^{-1}$
[2] - Less than detection level of 0.001 $mg.L^{-1}$
[3] - Contaminated

POWDER MILL LAKE TO LAKE WILLIAM

	pH	Pb[1] ($mg.L^{-1}$)	As ($mg.L^{-1}$)	Mn ($mg.L^{-1}$)	Al[2] ($mg.L^{-1}$)	Fe ($mg.L^{-1}$)	Ni[3] ($mg.L^{-1}$)
13 June	6.2	L	0.002	0.02	0.03	0.04	L
19 Aug.	6.5	0.002	0.0043	0.02	L	0.04	L
23 Nov.	6.9	0.002	0.0046	0.04	0.07	0.19	L
16 Feb.	6.4	L	0.0008	0.03	0.4	0.08	CON[4]

[1] - Less than detection level of 0.002 $mg.L^{-1}$
[2] - Less than detection level of 0.01 $mg.L^{-1}$
[3] - Less than detection level of 0.001 $mg.L^{-1}$
[4] - Contaminated

LAKE WILLIAM TO LAKE THOMAS

	pH	Pb[1] ($mg.L^{-1}$)	As ($mg.L^{-1}$)	Mn ($mg.L^{-1}$)	Al ($mg.L^{-1}$)	Fe ($mg.L^{-1}$)	Ni[2] ($mg.L^{-1}$)
05 May	6.6	L	0.0026	0.03	0.065	0.07	L
14 June	6.3	0.002	0.0024	0.03	0.045	0.06	L
19 Aug.	6.3	L	0.0021	0.02	0.015	0.03	L
22 Nov.	6.6	0.003	0.0022	0.09	0.11	0.21	L
16 Feb.	6.4	L	0.0021	0.04	0.05	0.08	CON[3]

1 - Less than detection level of 0.002 $mg.L^{-1}$
2 - Less than detection level of 0.001 $mg.L^{-1}$
3 - Contaminated

LAKE THOMAS

	Depth	DO ($mg.L^{-1}$)	pH	Pb[1] ($mg.L^{-1}$)	As ($mg.L^{-1}$)	Mn ($mg.L^{-1}$)	Al ($mg.L^{-1}$)	Fe ($mg.L^{-1}$)	Ni[2] ($mg.L^{-1}$)
05 May	1	11(est)	6.6	L	0.0024	0.03	CON[3]	0.05	CON
	4.5	11(est)	6.6	L	0.0027	0.04	CON	0.05	CON
	8	11(est)	6.5	L	0.003	0.03	CON	0.06	CON
14 June	1	9.3	6.5	L	0.0029	0.03	0.035	0.06	L
	6	8.9	6.5	L	0.0038	0.04	0.033	0.05	L
	11	8.0	6.3	L	0.0043	0.05	0.025	0.06	L
17 Aug.	1	8.6	6.5	0.004	0.004	0.02	0.01	0.03	L
	4	8.4	6.3	0.004	0.0058	0.03	0.01	0.02	L
	9	2.0	6.1	L	0.0040	0.94	0.015	0.05	L
	11	1.0	6.2	L	0.0043	1.3	0.015	0.14	L
23 Nov.	1	9.3	7.3	L	0.0037	0.07	0.035	0.06	L
	6	9.0	6.5	L	0.0042	0.07	0.035	0.07	L
	12	9.0	6.7	0.003	0.0034	0.07	0.027	0.06	L

[1] - Less than detection level of 0.002 $mg.L^{-1}$
[2] - Less than detection level of 0.001 $mg.L^{-1}$
[3] - Contaminated

LAKE THOMAS TO LAKE FLETCHER

	pH	Pb[1] ($mg.L^{-1}$)	As ($mg.L^{-1}$)	Mn ($mg.L^{-1}$)	Al ($mg.L^{-1}$)	Fe ($mg.L^{-1}$)	Ni ($mg.L^{-1}$)
05 May	6.4	L	0.0015	0.07	0.14	0.07	0.002
14 June	6.4	L	0.0022	0.09	0.083	0.08	0.0014
22 Aug.	6.3	L	0.0023	0.07	0.015	0.11	0.001
23 Nov.	6.5	L	0.0026	0.08	0.087	0.09	0.0012
16 Feb.	6.2	L	0.002	0.11	0.15	0.11	CON[2]

[1] - Detection level 0.002 $mg.L^{-1}$
[2] - Contaminated

LAKE FLETCHER

	Depth	DO ($mg.L^{-1}$)	pH	Pb[1] ($mg.L^{-1}$)	As ($mg.L^{-1}$)	Mn ($mg.L^{-1}$)	Al ($mg.L^{-1}$)	Fe ($mg.L^{-1}$)	Ni[2] ($mg.L^{-1}$)
26 April	1	11.3	6.4	L	0.0013	0.07	CON[3]	0.09	CON
	5	11.3	6.4	L	0.0013	0.06	CON	0.10	CON
13 June	1	8.8	6.2	L	0.0015	0.07	0.078	0.08	0.002
	3	8.9	6.1	L	0.0013	0.08	0.08	0.07	0.001
	7	8.3	6.4	L	0.0016	0.07	0.083	0.07	L
23 Aug.	1	8.5	6.4	0.004	0.002	0.03	0.01	0.02	L
	4	8.4	6.3	L	0.0018	0.03	0.01	0.02	L
	6	8.3	6.4	0.003	0.0018	0.04	0.01	0.02	L
22 Nov.	1		6.4	L	0.0022	0.07	0.08	0.11	0.0018
	3		6.5	L	0.0022	0.07	0.095	0.12	0.0016
	5		6.3	L	0.002	0.06	0.095	0.11	0.0017

[1] - Detection level 0.002 $mg.L^{-1}$
[2] - Detection level 0.001 $mg.L^{-1}$
[3] - Contaminated

PERRY LAKE

	Depth	DO ($mg.L^{-1}$)	pH	Pb[1] ($mg.L^{-1}$)	As[2] ($mg.L^{-1}$)	Mn[3] ($mg.L^{-1}$)	Al ($mg.L^{-1}$)	Fe ($mg.L^{-1}$)	Ni[4] ($mg.L^{-1}$)
05 May	1		6.2	L	L	L	CON[5]	0.02	L
15 June	1	8.3	6.2	L	L	0.01	0.053	0.02	L
16 Aug.	1		6.1	0.002	0.0003	0.02	0.022	0.02	L
1 Dec.	1		6.3	L	L	0.01	0.087	0.03	L

[1] - Less than detection level of 0.002 $mg.L^{-1}$
[2] - Less than detection level of 0.0002 $mg.L^{-1}$
[3] - Less than detection level of 0.01 $mg.L^{-1}$
[4] - Less than detection level of 0.001 $mg.L^{-1}$
[5] - Contaminated.

MUDDY POND TO LAKE THOMAS

	pH	Pb[1] ($mg.L^{-1}$)	As ($mg.L^{-1}$)	Mn ($mg.L^{-1}$)	Al ($mg.L^{-1}$)	Fe ($mg.L^{-1}$)	Ni[2] ($mg.L^{-1}$)
05 May	6.6	1	0.031	0.05	0.05	0.10	2
13 June	6.3	1	0.047	0.06	0.065	0.18	2
17 Aug.	6.5	1	0.027	0.08	0.035	0.25	0.001
23 Nov.	6.6	0.003	0.014	0.02	0.013	0.18	2
16 Feb.	6.3	1	0.0040	0.04	0.05	0.07	3

1 - Less than detection level of 0.002 $mg.L^{-1}$
2 - Less than detection limit of 0.001 $mg.L^{-1}$
3 - Contaminated